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PRIMARY ADHESIVELY BONDED STRUCTURE TECHNOLOGY (PABST)

Tooling, Fabrication and QA Report

DOUGLAS AIRCRAFT COMPANY
MCDONNELL DOUGLAS CORPORATION
LONG BEACH, CALIFORNIA 90846

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The Primary Adhesively Bonded Structure Technology (PABST) program's overall objective was to demonstrate significant improvements in cost, integrity, and durability of primary fuselage structures using latest adhesive bonding techniques, materials, and processes. Accordingly, this document summarizes the findings during Phase III, Fabrication, and details highlights of the Manufacturing and Quality Assurance effort in the areas of Tooling and Fabrication. Construction of the Full Scale Demonstration Component (FSDC) provides

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important performance comparisons of various bond tools, surface preparation techniques, adhesives, primers, bagging approaches and inspection methods. The fabrication of large constant and non-constant section bonded panels for the FSDC also provided invaluable manufacturing experience; established a natural testbed for validation of Phase II, Detail Design; and yielded excellent feedback for advancement of the PABST technology in Engineering, Materials and Process, and Quality Assurance.

FOREWARD

This report presents the results of the Tooling, Fabrication and Quality Assurance portion (Phase III) of the Primary Adhesively Bonded Structure Technology (PABST) program, Contract F33615-75-C-3016. The effort described herein was performed by the Douglas Aircraft Company, Long Beach, California, a division of the McDonnell Douglas Aircraft Corporation, with Mr. E.W. Thrall, Jr., as the Program Manager.

This work was sponsored by the Air Force Flight Dynamics Laboratory (AFFDL) under joint management and technical direction of AFFDL and the Air Force Materials Laboratory (AFML), Wright-Patterson Air Force Base, Ohio. This contract is administered as a part of the Advanced Metallic Structures, Advanced Development Programs (AMS ADP), Program Element Number 63211F, Project 486U. Mr. William R. Johnston is the Acting Program Manager and Mr. William L. Shelton is the Project Engineer (AFWAL/FIBAA) for the PABST program.

This work was performed during the period February 1975 to June 1979. Acknowledgment and appreciation is given to Lt. Col. Joseph S. Ford who served as the ADP Manager for this program during this period.

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SECTION I

INTRODUCTION

1.1 BACKGROUND

The Primary Adhesively Bonded Structure Technology (PABST) program is part of a long term structures Advanced Development Program (ADP) directed at stimulating advanced technologies in metallic aircraft structures and solving critical aircraft structural problems prior to acquisition of new weapon systems. The primary objective of this phase of the ADP is to improve the structural integrity and durability of future Air Force aircraft while providing significant cost and weight improvements through adhesive bonding.

Another important facet of the ADP concept is its requirement for a real-world baseline to speed the technological transition and enhance near-term payoff potential. Major advancements in surface treatment and adhesive technology in the early 1970's produced the new 250^{0}F cure adhesive systems which have greatly increased bond durability. As the timing of the PABST program coincided with the development of the Air Force Advanced Medium STOL Transport (AMST), this fuselage structure received considerable attention, especially since the emerging Air Force system has stringent design-to-cost requirements.

On 18 February 1975, the Air Force awarded the $18.4 million PABST contract to the Douglas Aircraft Company. This is a multidiscipline program, the primary objective of which is to achieve significant improvement in cost, weight, integrity, and durability of primary fuselage structure applicable to the AMST (Figure 1) and other wide-body transports through (1) the development and validation - ultimately by full-scale test - of adhesively bonded structure technology, and (2) the prompt and complete transfer of the knowledge and data obtained to the aerospace community. Implicit in the primary objective was the need to demonstrate manufacturing capability to produce large bonded fuselage structure and to verify that applications of adhesive bonding to primary structures can achieve the goals of a 20 percent cost saving and a concurrent 15 percent weight reduction when compared with existing fabrication techniques and conventional riveted structures.

Thus, two important questions to be answered by the $18,400,000 PABST investment are:

1. Can primary adhesively bonded structural components meet or exceed the strength, durability, and safety performance standards established for conventional (riveted) primary aircraft structures?

2. Can primary adhesively bonded components be manufactured cost effectively on a production basis to demonstrate at least a 20 percent cost savings and a 15 percent weight savings over comparable conventional primary components?

Because of the extreme criticality of primary structural components, it was deemed necessary to build a Full Scale Demonstration Component (FSDC) to expose the complete scope of problems that might be encountered in design, analysis, inspection, and manufacturing; and for validating by structural testing. Logic and economics dictated the construction of a bonded test component, 42 feet long and 18 feet in diameter. It is similar in shape, size and load profile to the fuselage of the Douglas AMST candidate, the prototype widebody military transport YC-15, Figure 1. Nearly 600 bonded assemblies and 94 mechanical assemblies were fabricated before assembly was started on the FSDC panels in order to fully assess the applicability of the technology to the entire fuselage. In stress cycle tests, the FSDC was an unqualified success and the bonded panels proved to be structurally equivalent to, or better than, comparable conventional riveted panels. The conclusions and recommendations in Section 5 list the highlights learned during the PABST program.

Because this is strictly a manufacturing and quality assurance oriented report, the purpose is to document primarily Phase III-Fabrication, by describing what was done; why; results; and recommendations for future production efforts. The program consisted of four activity phases, summarized as follows.

FIGURE 1. DOUGLAS AMST CANDIDATE – WIDE-BODY TRANSPORT (YC-15)

1.1.1 Phase IB - Preliminary Design

The prime goal was to minimize manufacturing complexities and subsequently costs by making careful and detailed comparative factors studies during the conceptual design phase. Many concepts were comprehensively evaluated such as the number of parts required, simplicity of parts, concept and cost of tools required, bonding layup operations, amount of critical and close tolerance machining operations, ease of inspection, and ease of making repairs. These provided the basis for the design-to-cost-approach goal governing this program. Many test specimens were fabricated during this phase to help evaluate design concepts and guide in establishing effective manufacturing procedures. In addition, environmental testing of the surface treatment and adhesive systems was initiated.

1.1.2 Phase II - Detailed Design

The Manufacturing Plan was updated to match the selected Engineering design. This revised plan detailed the method of manufacture selected at the conclusion of the engineering design study and evaluation of test panels. Techniques, processes, materials, procedures and tooling considerations developed in the evaluation phase, Phase IB, were incorporated into the Manufacturing Plan. Phase II also encompassed planning, tool design and procurement tasks. All FSDC drawings for all phases were "signed-off" by representatives of Manufacturing, M&PE, and QA to assure manufacturing and inspection capability.

1.1.3 Phase III - Fabrication

The refined Manufacturing Plan was implemented and fabrication and assembly of the FSDC was completed. In addition to fabricating the test panels and the bonded assemblies for the FSDC, hot bonded repairs (without rivets) of major damage to a large pressure panel were performed and demonstrated by cycle testing to four design lifetimes. This operation confirmed the feasibility of the non-tank phosphoric acid anodize surface treatment developed by Boeing in a parallel program as referenced in AFML-TR-77-206/AFFDL-TR-77-139. Boeing also successfully performed hot bonded repairs on a large PABST test panel, supplied by Douglas, as referenced in AFFDL-TR-78-79.

1.2 CHARTER OF MANUFACTURING RESEARCH AND DEVELOPMENT

The charter of the Manufacturing Research and Development (MR&D) section in the PABST program was to develop manufacturing methods and tooling, and then select and coordinate the most promising manufacturing approach, techniques, and tooling to ensure best utilization of 30 years of industry experience with adhesive bonding involving secondary and primary structures. Our goal was to build upon previous successes with secondary bonded structures and advance the state of the adhesively bonded structural technology to the point of validating its feasibility for more widespread use in primary structures. To determine the feasibility of producing primary bonded

structures on a cost-effective production basis was considered the goal of the manufacturing effort.

Specifically, the MR&D section responsibility was to provide the facilities and perform the function of linking Engineering and the Materials and Process test labs to the fabrication of hardware in a limited production environment.

1.3 HISTORY AND CHRONOLOGY

The use of adhesive bonding in components of aircraft structure has increased so dramatically over the last 15 years that most aircraft delivered today utilize the technology to some degree. Generally, these applications have been limited to secondary structures where adhesive bond strength is much greater than the strength of the metal parts bonded together. Experience with these secondary structures led to recognition that the problems of adhesive bond durability, tooling, fabrication, inspection, and the effects of defects must be resolved before more extensive use can be made of adhesive bonding on primary structures. Adhesively bonded structures on some existing aircraft have experienced environmental degradation at the bond interface, particularly with the first generation of 250^{0} cured modified epoxies. Moisture entering the bond through edges and around fasteners has caused exfoliation and crevice corrosion after the adhesive has been disbonded from the surface.

This has been attributed to inadequate surface preparation and protection, and the hygroscopic nature of the first generation adhesives. It became apparent during the PABST testing that some of these durability problems were also associated with the bonding of clad 7075 aluminum alloys.

Extensive government and industry exploratory development programs have resulted in improved adhesives, primers, surface preparation techniques, and treatments. In addition, nondestructive inspection and manufacturing techniques for adhesive bonding have been vastly improved.

Adhesive bonding has been used for 30 years to fabricate secondary structures such as ailerons, gear doors, trim tabs, flap vanes, etc. These

applications often consisted of honeycomb with 0.012, 0.016, and 0.020 inch thick aluminum skins. Another frequent application of metal bonding is the use of finger doublers to improve the sonic fatigue resistance of control surface skins and trailing edge panels.

Likewise, there are many applications of bonded/beaded panels in thin sheet aluminum. By nature, the primary structures have more stringent strength and durability requirements than do secondary structures.

1.4 MANUFACTURING CONSIDERATIONS FOR BONDING PRIMARY STRUCTURE

Several aspects of adhesive bonded primary structure had to be considered prior to bonding the FSDC. Stemming largely from the increased size of the bonded assemblies and the thicker gages of the metal details, the initial areas of concern for manufacturing were:

- o Selection of bonding tool concept(s) for both simple and compound curvature.
- o Detail fabrication tool tolerances.
- o Tooling materials selection.
- o Uniformity of detail parts.
- o Control of adhesive bond thickness, voids, porosity and flash.
- o Developing bagging techniques.
- o Understanding process control and handling constraints.
- o Verification that an assembly of details is complete, fits together properly, and is ready to process and bond.
- o More severe rework consequences of a design or durability deficiency in bonded primary structure than for secondary.

In addition, the following three factors were initially believed to be more critical for primary structure than for riveting or for bonding of secondary structure and were treated as such at the start of the program. In all cases this proved to be an unwarranted assumption.

- o Tighter detail part tolerances.
- o More stringent flaw requirements than for secondary structure.
- o Catastrophic structural consequences resulting from imperfections in fabrication.

SECTION II

FSDC AND BONDED JOINTS

2.1 FULL SCALE DEMONSTRATION COMPONENT

As previously stated, the FSDC, built to validate adhesive bonding for primary structure, was actually patterned after the AMST (YC-15) fuselage. The section constructed was 42 feet long, 18 feet in diameter and extended from the forward part of the cargo compartment to a station 24 inches aft of the main fuselage frame which supports the landing gear and the rear wing spar, Figures 2, 3-a and 3-b. The compound-curved nose section was modified to make it axisymmetric to reduce tooling costs. However, no manufacturing problems which would have to be faced in producing a real bonded aircraft were overlooked. The challenge of fitting the curved and twisted floor longerons to the skin was just as severe. Figures 4, 5, 6, and 7 show the actual major assembly sequence as outlined in Figure 8.

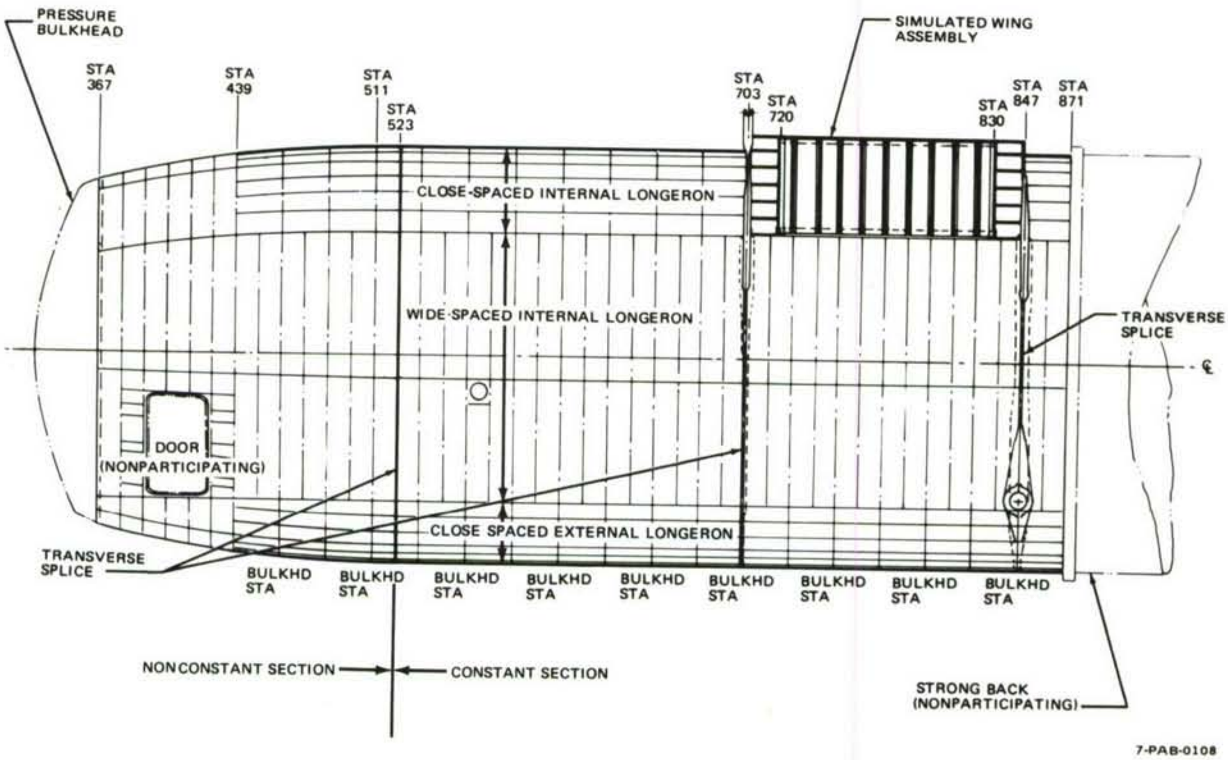


FIGURE 2. FULL SCALE DEMONSTRATION COMPONENT

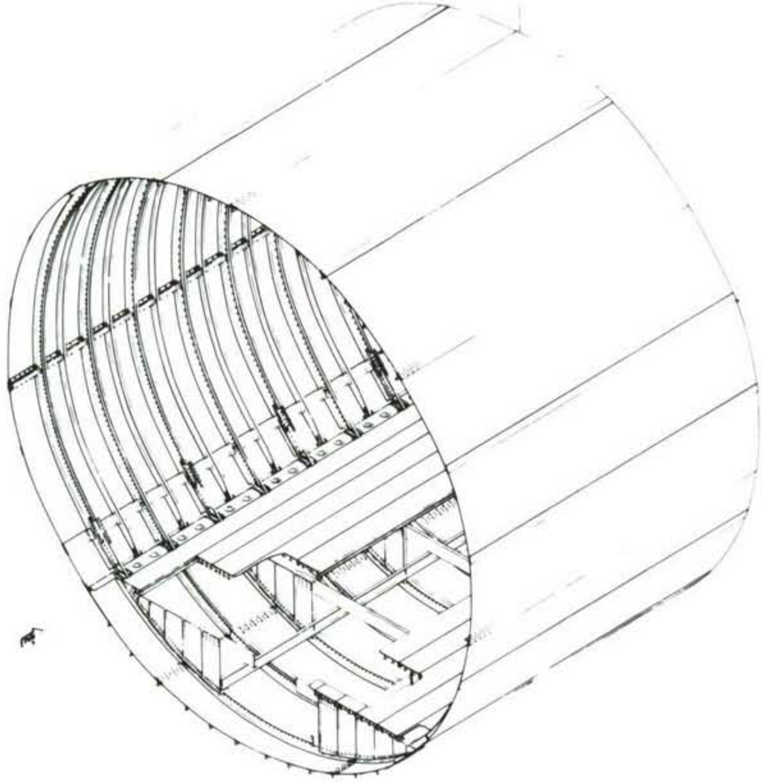


FIGURE 3-a. PERSPECTIVE OF FULL SCALE DEMONSTRATION COMPONENT

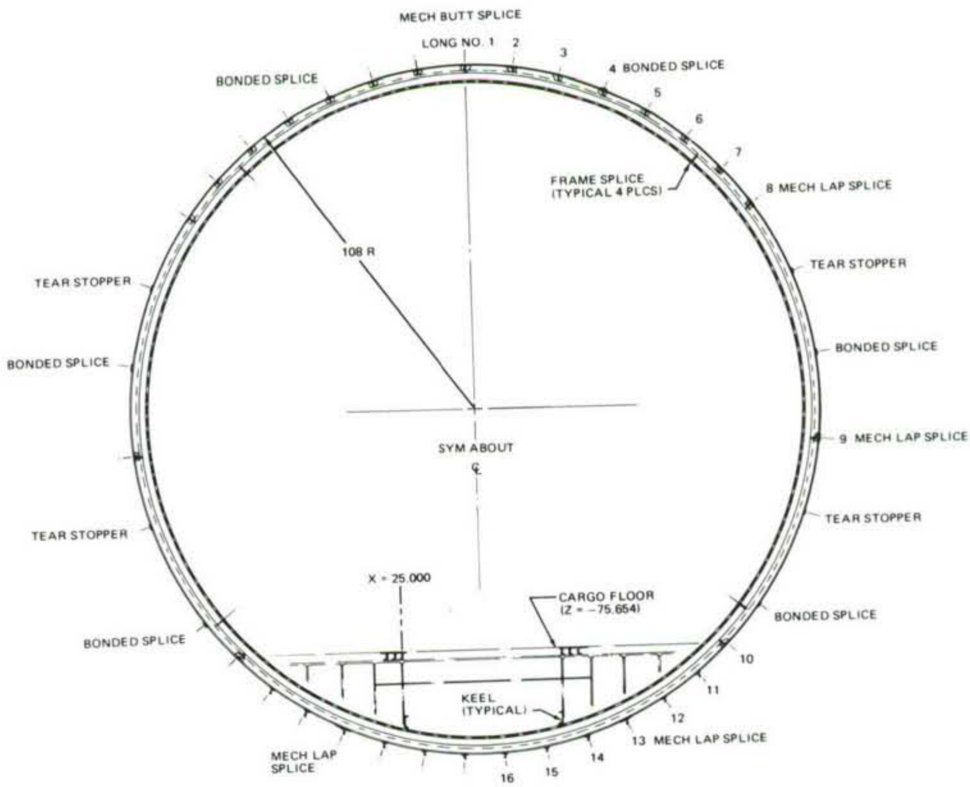


FIGURE 3-b. CROSS SECTION OF FSDC

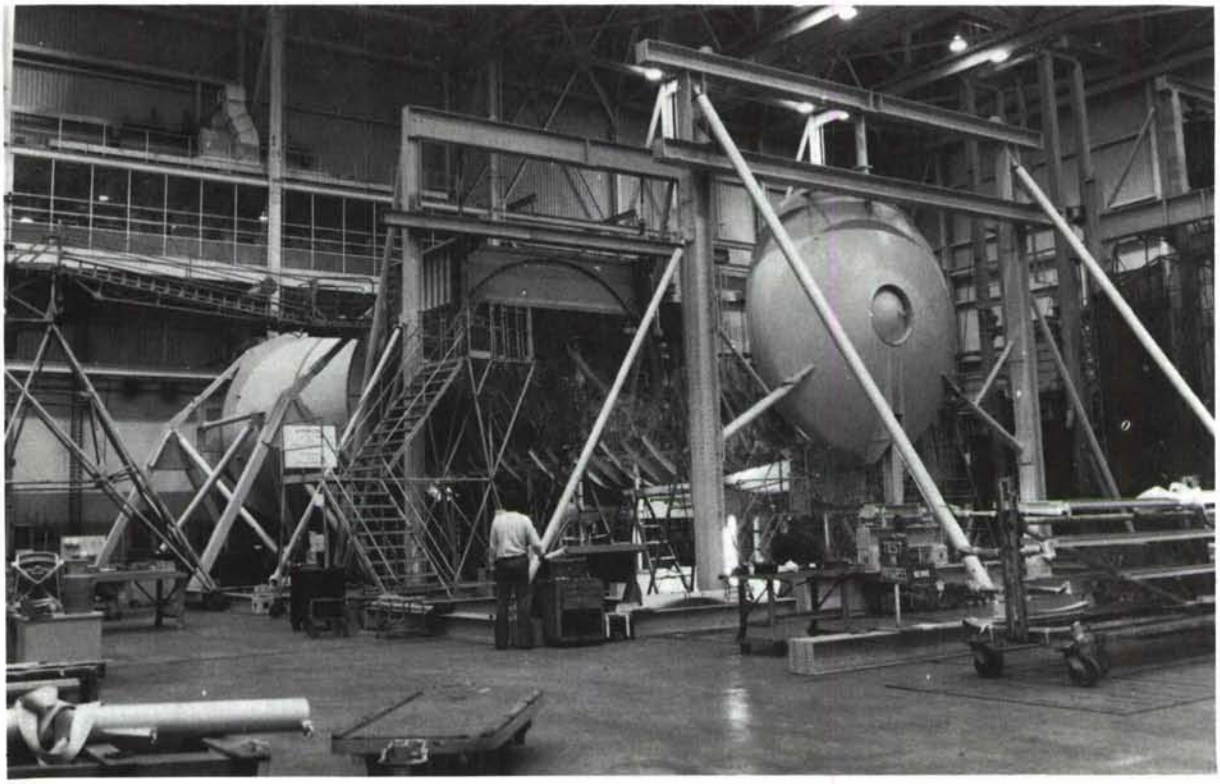


FIGURE 4. CRADLE SUPPORT STRUCTURE

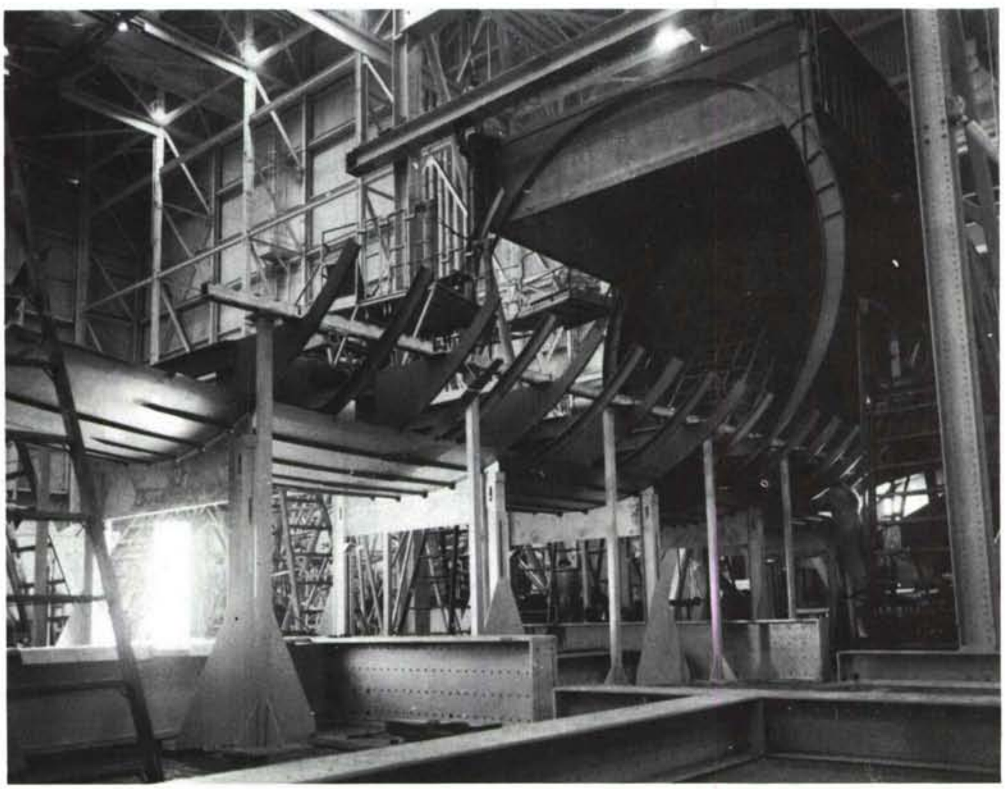


FIGURE 5. BOTTOM CONSTANT SECTION AND LOWER NONCONSTANT SECTION PANELS

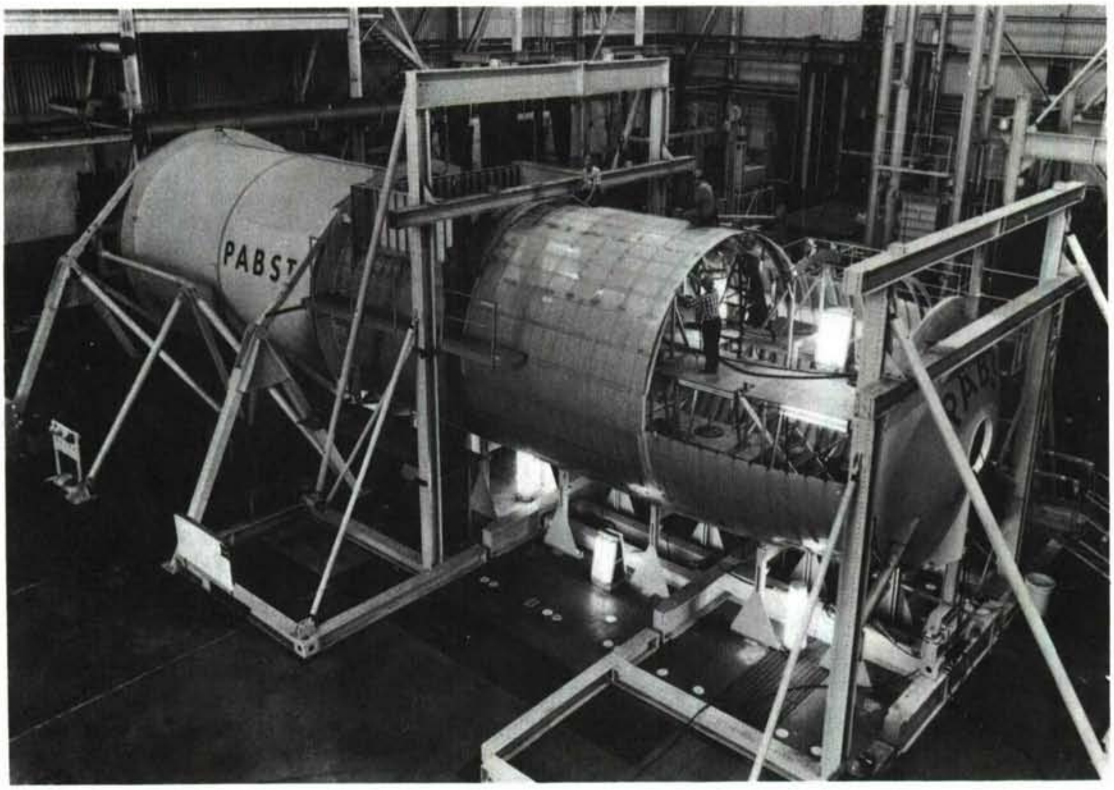


FIGURE 6. FLOOR PLANK AND INTERNAL PLATFORM INSTALLATION

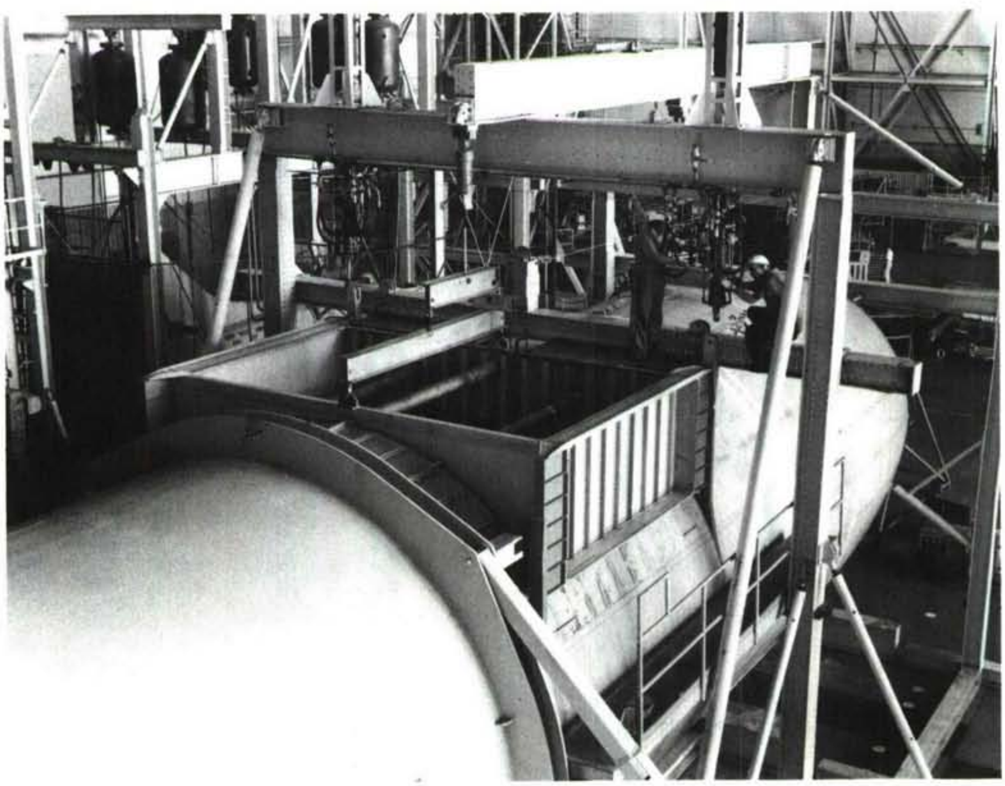


FIGURE 7. WING BOX AND SPAR FRAMES INSTALLATION

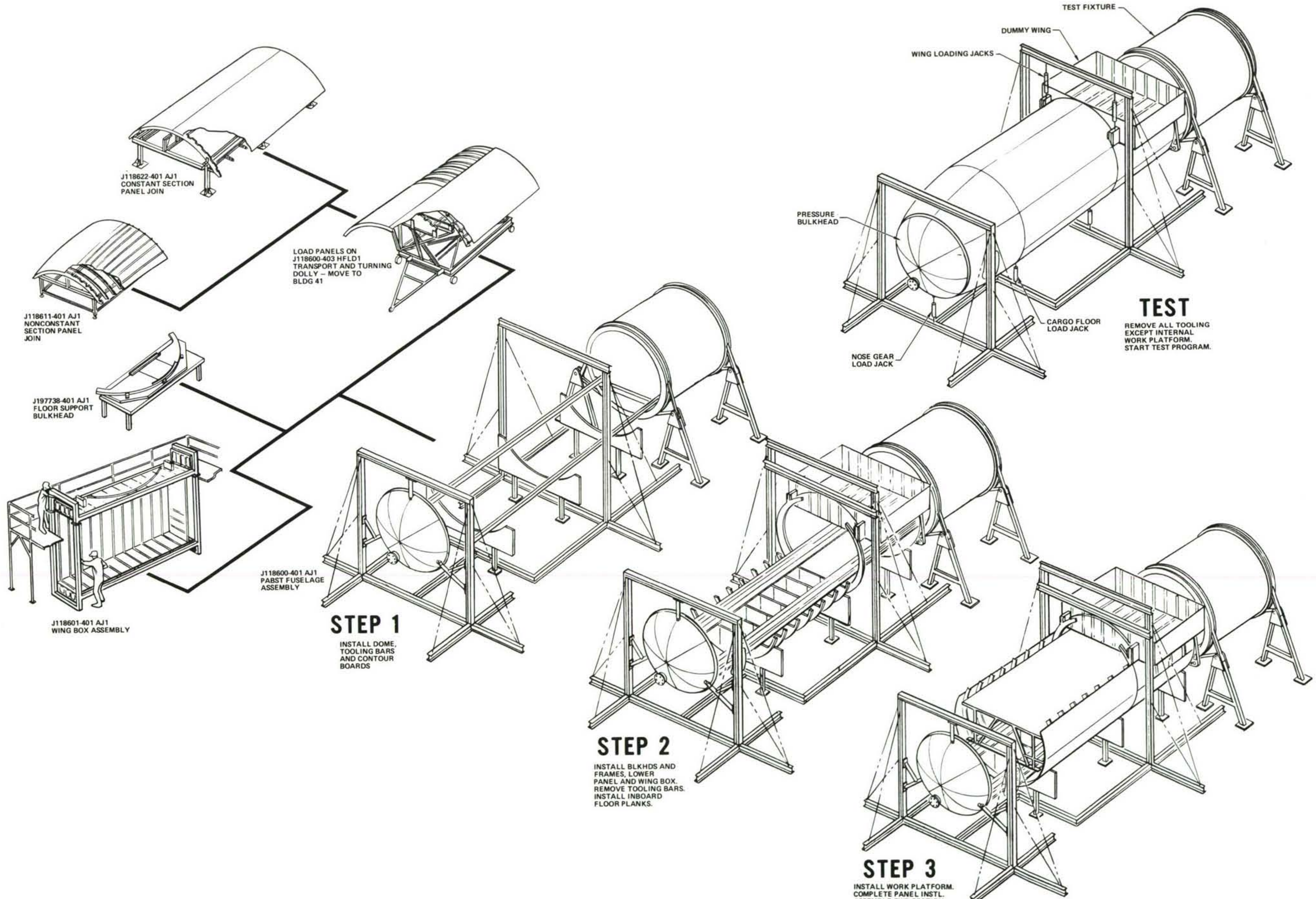


FIGURE 8. ASSEMBLY BREAKDOWN AND WORK FLOW

The structural members and assemblies that make up the FSDC were designed to the static, fatigue, and damage tolerance criteria established during preliminary design phases 1B and II. Since minimum cost was a PABST goal, the frames and longerons were sized to carry the design loads with the least number of different extrusion shapes. Mechanical fastening was used to join the bonded panels together. The FSDC was designed and tested for four lives of fatigue and met the damage tolerance criteria of MIL-A-83444. The mechanical splices employed adhesively bonded external doublers to prevent the need for deeply countersinking holes in the loaded skin. Intercostals were added to stabilize all frames and to provide axial load capability to the nose section. The FSDC has both mechanical and bonded skin splices in the longitudinal and circumferential directions. All fasteners that penetrated the exterior skin were installed with wet sealant and the faying surfaces were sealed with MIL-S-81733 sealant. This procedure ensured a pressure seal and protected the joint from moisture and is the same as would be used for a production assembly.

At the start of the PABST program it was decided to minimize the number of mechanical splices by making panels as large as the autoclave would permit. Within each such panel, double-strap bonded splices were therefore used to make up for the difference in width between the stock sizes and the autoclave diameter. This provided an opportunity to compare the fatigue performance and manufacturing problems associated with bonded and mechanical splices. It had been felt originally that a design using very large bonded panels was the optimum method from a cost standpoint.

Further consideration needs to be given to the issue of just what is the best width of panel to bond. By nesting slightly smaller panels inside each other, the square footage bonded per autoclave cycle can be increased considerably beyond that of the single largest panel any specific autoclave could handle. One must also consider the question of transporting, handling, and storing the details and bonded assemblies; and also resolve the issue of using premium width sheets or using standard width sheets with many extra bonded splices.

The mechanical splices at the manufacturing breaks were designed to be of single-lap configuration primarily to obviate any need to trim-on-assembly with the resulting break in the anodize protection; however, all panels were in fact trimmed on assembly. A secondary benefit was a substantial cost saving with respect to double-strap joints, which would have entailed twice as many fasteners and trimming on assembly where they butted together. With the single-lap joints, the tolerances were absorbed simply by adjusting the overlap slightly. The single exception was the double-strap splice at the top centerline, for which the tolerances were absorbed at longeron No. 8, on the opposite sides of each panel.

There are three different skin panel designs on the FSDC: 1) the internal close spaced longeron panels located in the upper third of the fuselage, Figure 9; 2) the external close spaced longeron panels located in the lower section of the fuselage, Figures 10-a and 10-b; and 3) the wide spaced longeron panels located at the fuselage sides, Figures 11-a and 11-b. These different designs have structural justification in their own right.

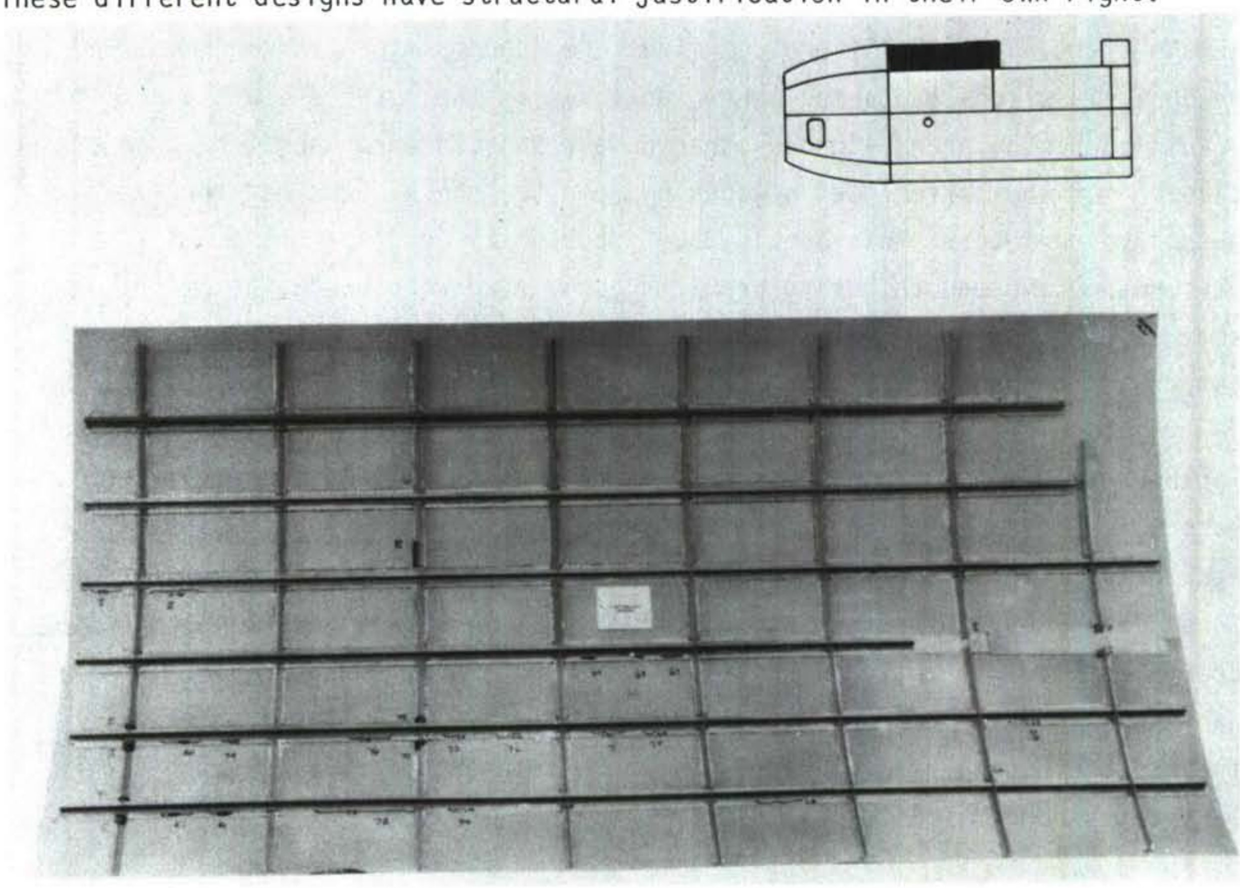


FIGURE 9. INTERNAL CLOSE-SPACED LONGERON PANEL

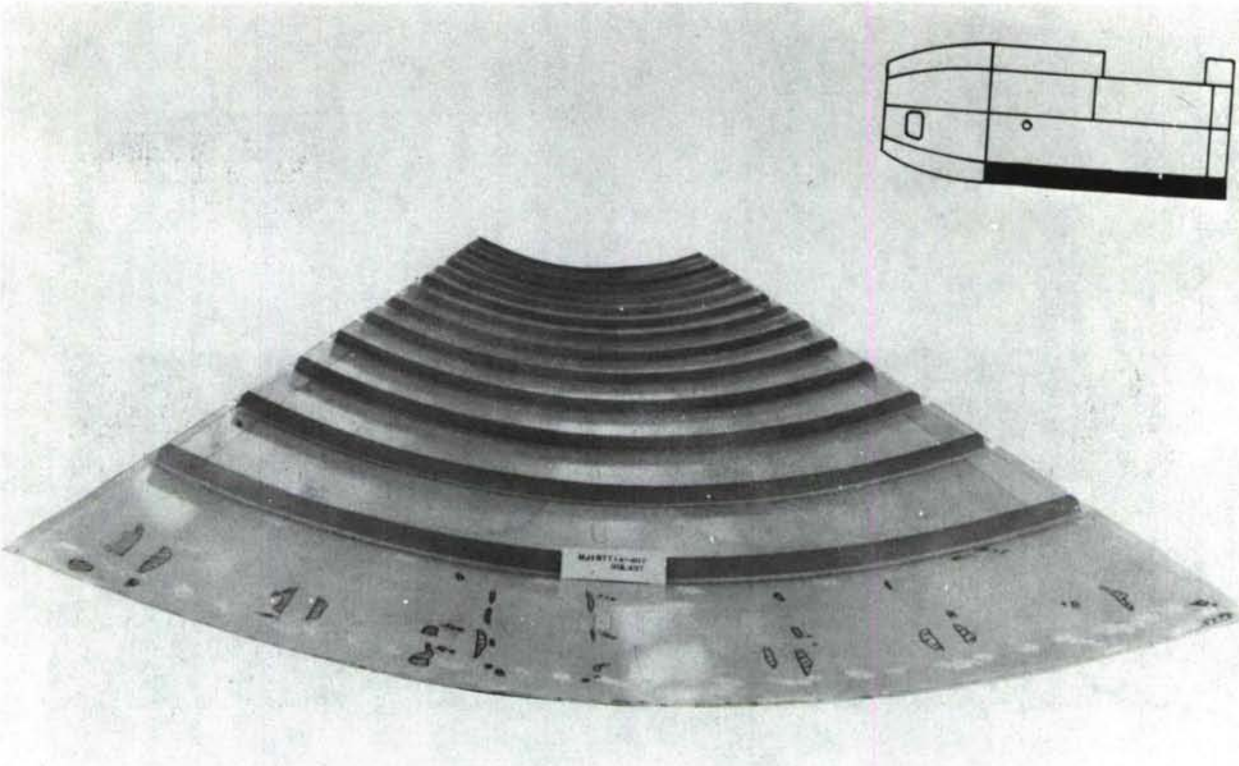


FIGURE 10-a. INTERNAL SIDE OF EXTERNAL CLOSE-SPACED LONGERON PANEL

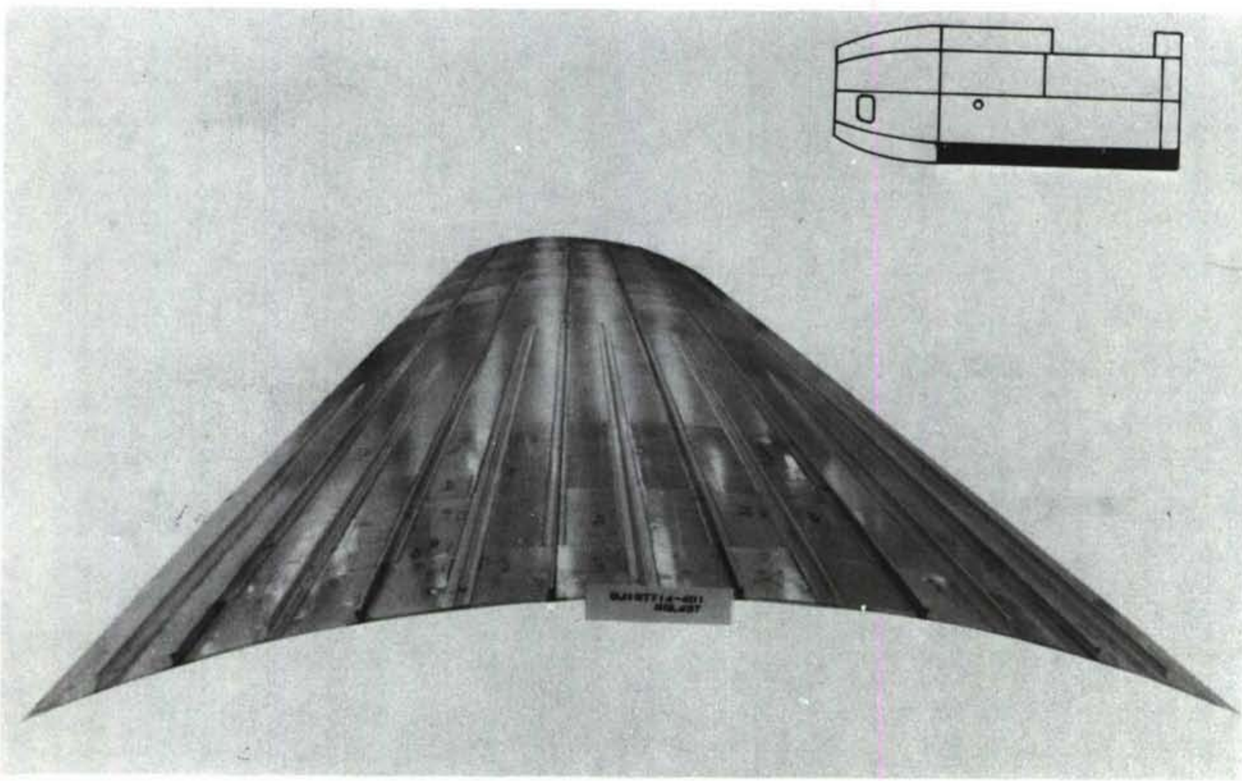


FIGURE 10-b. EXTERNAL CLOSE-SPACED LONGERON PANEL

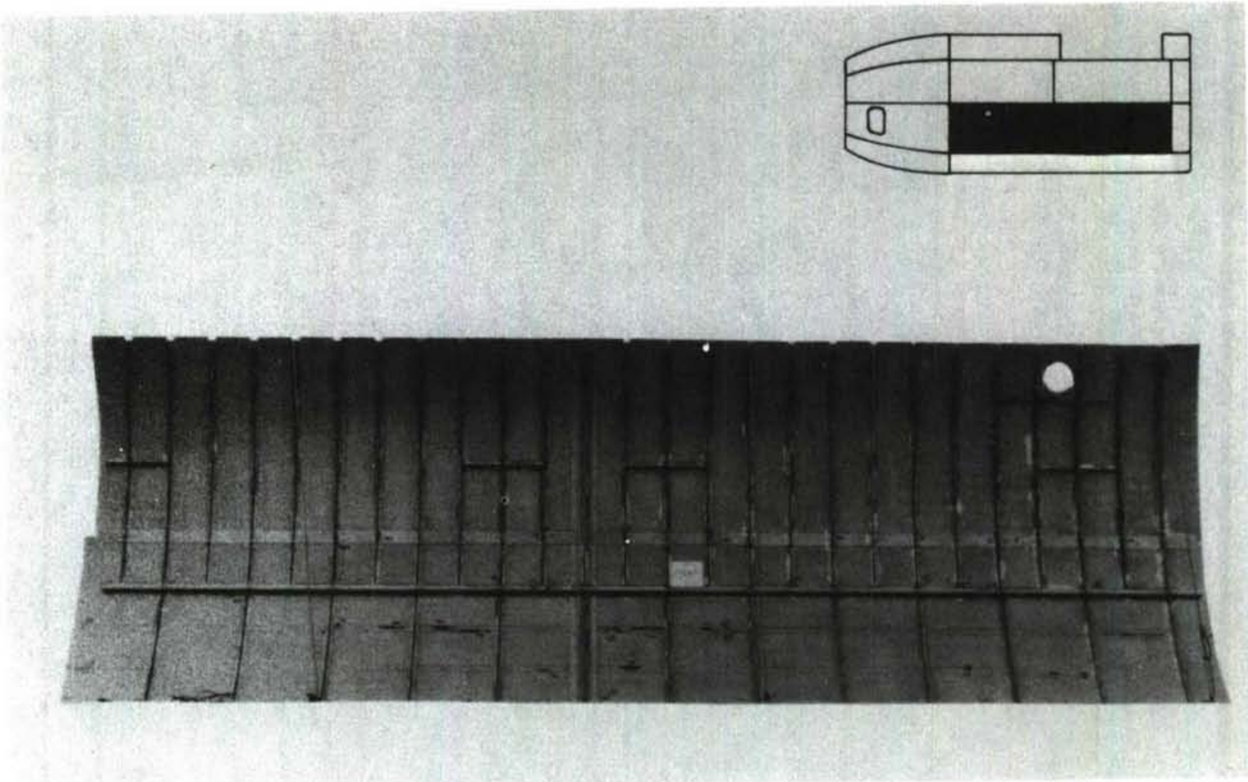


FIGURE 11-a. INTERNAL SIDE OF WIDE-SPACED LONGERON PANEL

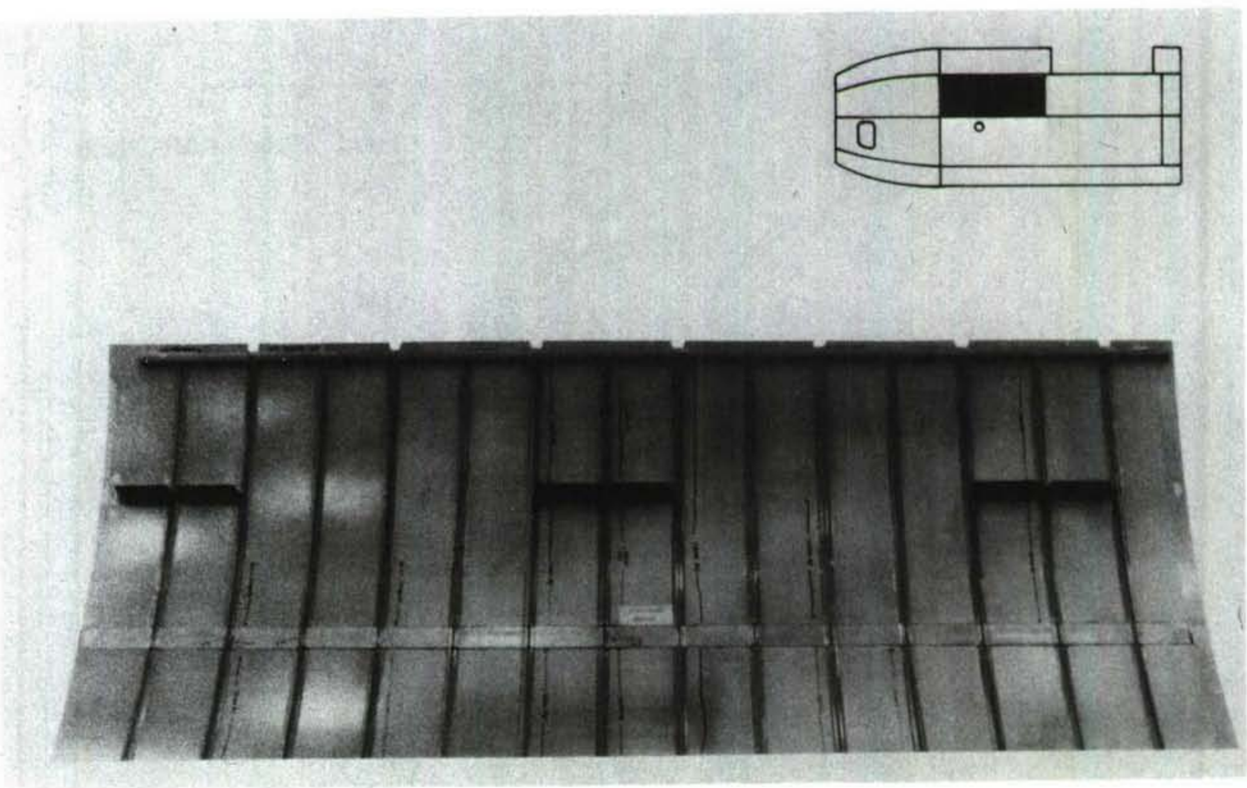


FIGURE 11-b. INTERNAL SIDE OF WIDE-SPACED LONGERON PANEL

In addition, such a choice provided an opportunity to compare designs and learn much more about the manufacturing of bonded assemblies than would have been the case had there been standardization on a single concept all over the structure.

2.2 FUSELAGE SKIN PANELS

Bonded panel assemblies varied in overall dimensions in the longitudinal (fore and aft) and transverse (circumferential) directions, Figure 12. Panel boundaries were selected to maximize the longitudinal and transverse dimensions while proper attention was given to manufacturing and tooling constraints and fuselage configuration requirements. The autoclave size limited the panel arc length (transverse dimension) to 113 inches and the longitudinal dimension to just under 30 feet. In addition, vendor manufacturing constraints limited skin width to 94 inches for .050 to .071 inch thick skins.

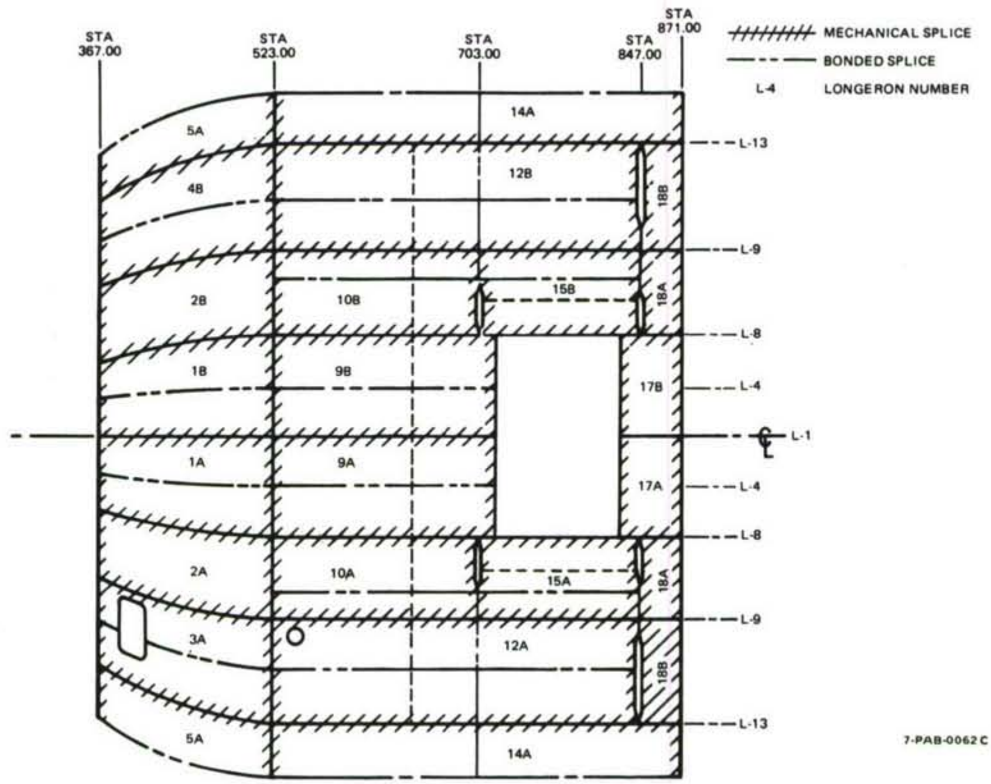


FIGURE 12. PANEL, SPLICE-TYPE AND LONGERON LOCATIONS

Final assembly sequence of the bonded panels basically started with the bottom panels (5A and 14A) which covers the area from longeron No. 13 left to longeron No. 13 right, Figure 12. These panels were installed first in the fuselage assembly fixture and were designed to be cradled in the fixture; which thus eliminated the bottom centerline splice and therefore simplified the tooling. The bonded panel assembly width was the maximum available sheet width. Due to autoclave width limitations and natural manufacturing breaks at longeron No. 8; panels 1A, 1B, 9A, 9B, 17A and 17B were spliced at the top of the fuselage centerline, Figure 12. The flush circumferential mechanical splice provided at the boundary between the constant section and the double-contoured nonconstant section allows tooling to be simplified and also simulate a manufacturing break as required for a production fuselage.

2.2.1 Constant Section Panels

Typical constant section close spaced internal longeron panel assemblies 9A and 9B extended from Station 523 to Station 720, and from longerons No. 8-left to No. 8-right. The panels consisted of both left and righthand bonded assemblies joined mechanically at longeron No. 1 (top centerline). Each bonded assembly included longitudinal stiffeners (extruded J-section longerons) and a bonded tear-stopper under each longeron so that the notches in the frame shear tees would terminate on a tear-stopper rather than on an unreinforced skin. This feature improved both fatigue resistance and damage tolerance. These 7075-T76511 extruded aluminum longerons were spaced approximately 15 inches on center. The basic skin thickness of 0.071 inch was chem-milled to 0.060 inch between longerons in the forward half of the panel. Additional doublers were bonded externally to the aft end of the panel to carry the high shear loads induced from the front spar.

Typical constant section close spaced external longeron panel, 14A, extended from Station 523 to Station 871, and from longerons No. 13-left to No. 13-right. It measured approximately 8 feet wide by 29 feet long and the longerons were bulb T-sections.

The longerons were spaced approximately 13.5 inches on center, with additional external longerons added at the aft end of the panel to interface with the test fixture. Internal and external doublers were bonded to the aft section of the panel to provide an interface with the strongback test fixture. Due to the length of the panel, a transverse bonded skin splice was located at Station 703.

A typical constant section side panel, 10A, differed in structural arrangement from the top and bottom panels in that there were twice as many frames and very few longerons. Consequently, these panels contained very few stiffener intersections which simplified the bagging operation. Longerons were wide spaced from No. 8 to No. 9 and from No. 9 to No. 10. In the longitudinal bonded skin splice, the external splice doubler was uninterrupted over the entire length of the panel while internal splice doublers were interrupted and joggled on top of frame tees. The 7475-T761 external tear-stoppers, 0.071 thick by 3.00 inches wide were bonded longitudinally to provide added fail-safe capability in the panels. Additional light frames and frame tees between full-depth frames strengthened the structure and increased the initial buckling resistance of the skin. These intermediate frames reduced panel width to 12 inch segments, in what would otherwise have been 24 inch wide panels. Intercostals and straps were located between longerons to stabilize each frame.

2.2.2 Nonconstant Section Panels

All longerons aft of and including Station 439 were identical to those in the corresponding constant section panels. All longerons ended at Station 439. Forward of Station 439, at longeron locations No. 1, 4, 8, and 9, full-depth intercostals provided axial load capability for the panel as shown, Figure 13. The frames aft of Station 439 were similar to the constant section frames in size and spacing. The frames from Station 439 forward were full-depth with no cutouts for longerons, and were spaced at 12 inch intervals.

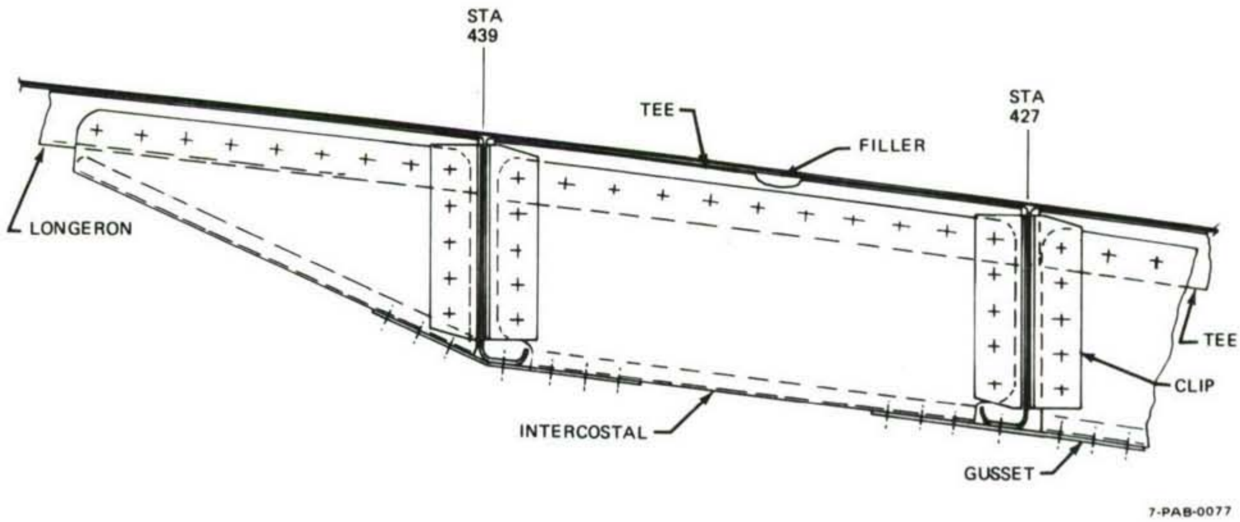


FIGURE 13. TYPICAL INTERCOSTAL CONSTRUCTION IN THE NONCONSTANT SECTION

A typical nonconstant section close spaced internal longeron panel assembly was joined mechanically at longeron No. 1 and No. 8. This internal longeron panel section extended from Station 523 forward to Station 367. The bonded skin splice at longeron No. 4, which extended the full length of the panel, contained a continuous 2024-T3 external splice member measuring 0.050 inch thick by 3.50 inches wide. Forward of Station 439 there was an interrupted internal splice member of the same dimensions. The internal splice was located between the frame tees, and also served as a filler for the intercostal tee that was bonded across the base legs of the frame tees.

A typical nonconstant section external longeron panel assembly extended from Station 367 to Station 523, and from longeron No. 13-left to No. 13-right. It was similar to the upper panel except that the longerons were bonded on the outside surface of the skin. The longerons were bulb T-sections, identical in cross-section to the external longerons used in the constant section panels, and the frame shear tees were continuous; i.e., the base leg was uninterrupted across the longerons.

NOTE

Aerodynamically, wind tunnel tests showed that the external longerons would not adversely affect stability or performance of the aircraft, and a primary advantage of this design was the relief it provided from the entrapment of bilge fluids and other corrosive substances.

A typical nonconstant section side panel with wide spaced longerons extended from Station 367 to Station 523, and from mechanically fastened longeron No. 8 to mechanically fastened longeron No. 9. The one-piece skin was 0.050 inch thick 2024-T3 bare aluminum alloy. The two tear-stoppers were 7475-T761, 0.071 inch thick and three inches wide. Intercostals were located at tear-stopper No. 2 (approximately two feet above longeron No. 9) in alternate bays to stabilize the frames. Doublers, 0.016 inch thick, were added near Station 523 to increase the skin thickness to 0.066 inch where countersunk mechanical fasteners were installed.

The panel on the left side, between Stations 367 and 523, and longeron No. 9 to longeron No. 13 had special constraints imposed on it. Besides limiting its size to the autoclave capacity, a large door was designed into the panel to include the "real" airplane anomaly of a crew entrance door with a door jamb and its unique internal stress distribution. This anomaly provided Manufacturing with the opportunity to bond the door jamb stiffening elements to the skin and two doublers, with a total maximum thickness at the edge of the door jamb of 0.355 inches. The 2024-T3 doublers which encompassed the door cutout were stretch formed from an 0.250 inch thick plate which was step-chem-milled to an integral header 0.125 inch thick and provided an 0.050 inch thick skin aft of Station 439, Figure 14. The door cutout was 32 inches by 60 inches and was located between Station 391 and Station 427 and from longeron No. 9 to longeron No. 10. All chem-milled steps were external. The door corner external doublers were also chem-milled from 0.180 inch stock and bonded to the exterior surface of the skin which is 0.125 inch thick in this area. The outermost doubler at the door cutout, along the upper and lower edges, was a 0.050 inch constant thickness bonded sheet. The bonded longitudinal skin splice on the panel was at mid-door level on one side, and at longeron No. 12 on the other. The 0.050 inch thick skins were spliced with an inner and outer bonded splice member. The thick skins were chem-milled at the splice and a third splice member was added between the skin and outer splice to improve the strength of that bonded joint.

Nearly 600 bonded assemblies and 94 mechanical assemblies were fabricated before assembly was started on the FSDC. A total of 22 bonded panel assemblies was used to build the complete FSDC.

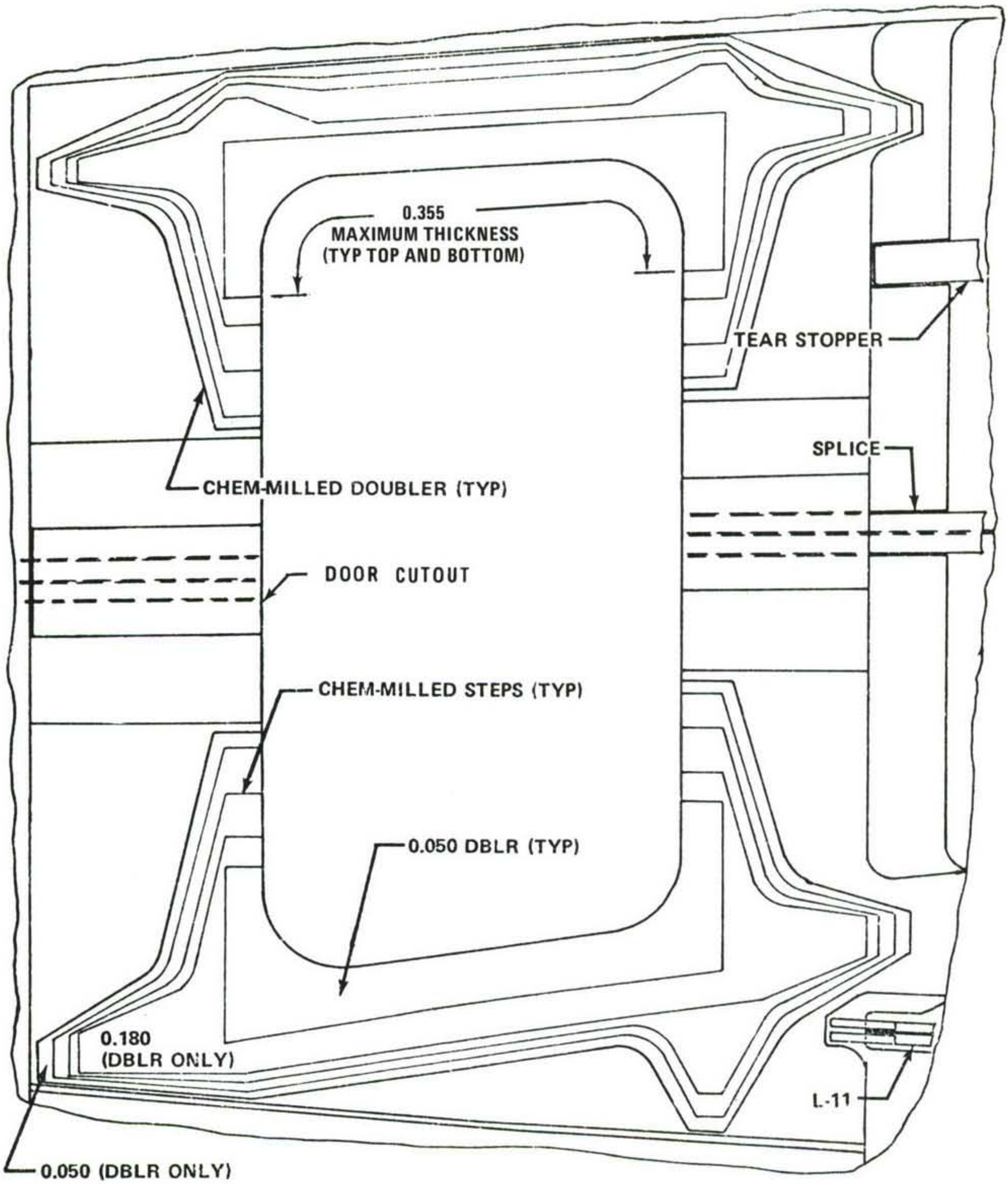


FIGURE 14. DOOR CORNER DOUBLERS (LOOKING INBOARD)

2.3 BONDED JOINTS

This section briefly describes the various bonded joints used in construction of the FSDC. Mechanical skin splices are shown in Figures 15-a, 15-b, 15-c and 15-d. It should be noted that adhesive bonding and sealant were used in these joints. The longitudinal bonded splices were fabricated in conformance with the design shown in Figure 16. Figure 17 shows the transverse bonded splice used at Station 703.

The frame-longeron intersection, Figure 18, was a major manufacturing concern. Specifically, where the frame shear tee is notched to permit the internal longeron to pass through uninterrupted. The addition of the crack stopper requires that the frame shear tee be joggled over the tear stopper. The joggled shear tee requires quality forming to ensure a good bond to the tear stopper. In general, the manufacturing quality of the stiffening detail parts requires detail fit tolerances equivalent to mechanically fastened structure in order to achieve an acceptable bondline.

The typical arrangements of details for bonding the frame shear tees to the skin are shown in Figures 19-a, 19-b, and 19-c which also show how the frames are mechanically joined. The bonded longeron joints are shown in Figures 20-a, 20-b, and 20-c.

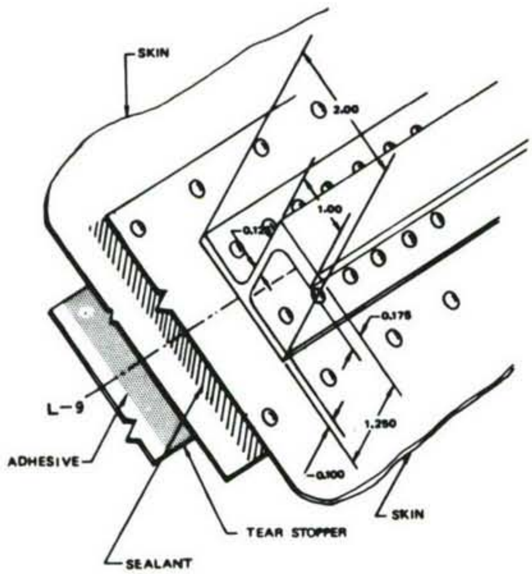


FIGURE 15-a. TYPICAL MECHANICAL OVERLAP SKIN SPLICE, LONGERON NO. 9

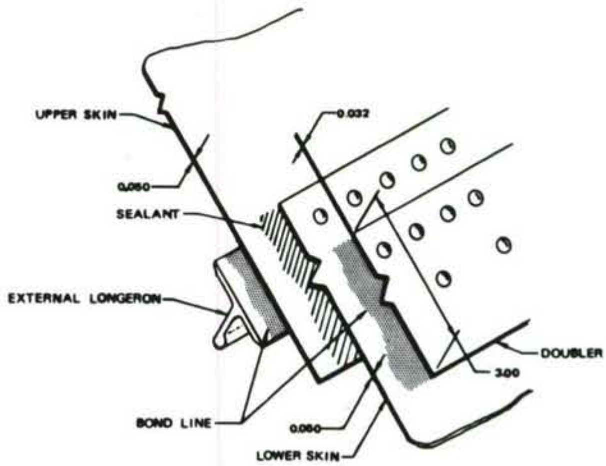


FIGURE 15-b. TYPICAL MECHANICAL OVERLAP SKIN SPLICE, LONGERON NO. 13

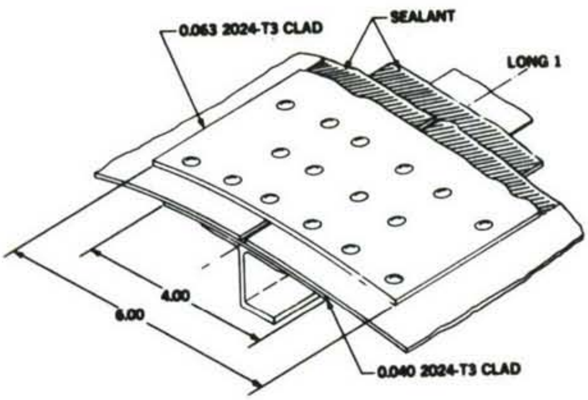


FIGURE 15-c. FORWARD FUSELAGE NON-CONSTANT LONGITUDINAL MECHANICAL SPLICE (TOP ℄ ONLY)

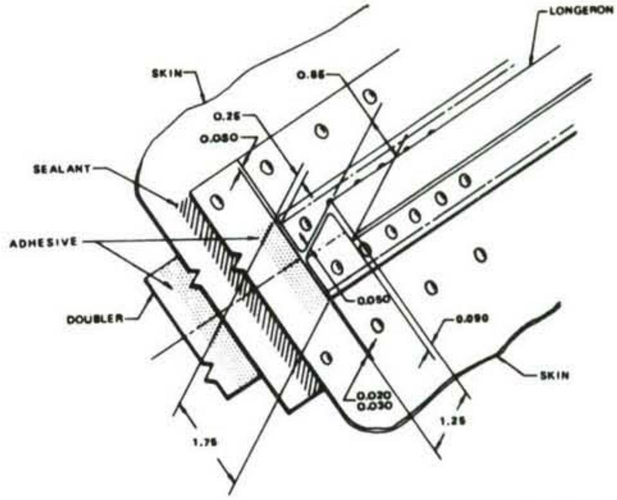


FIGURE 15-d. TYPICAL MECHANICAL OVERLAP SKIN SPLICE, LONGERON NO. 8

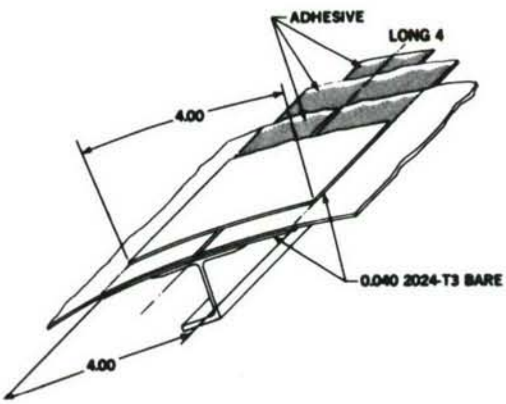


FIGURE 16. LONGITUDINAL-BONDED SPLICE

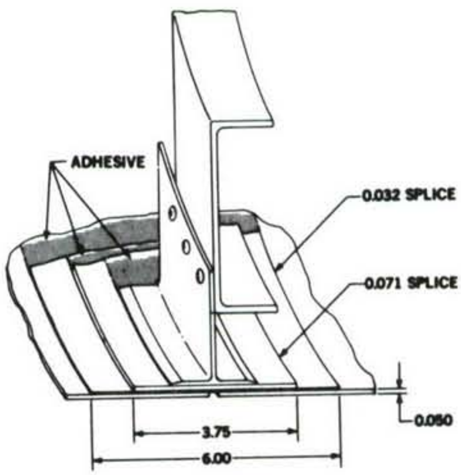


FIGURE 17. TRANSVERSE-BONDED SPLICE (STA 703 ONLY)

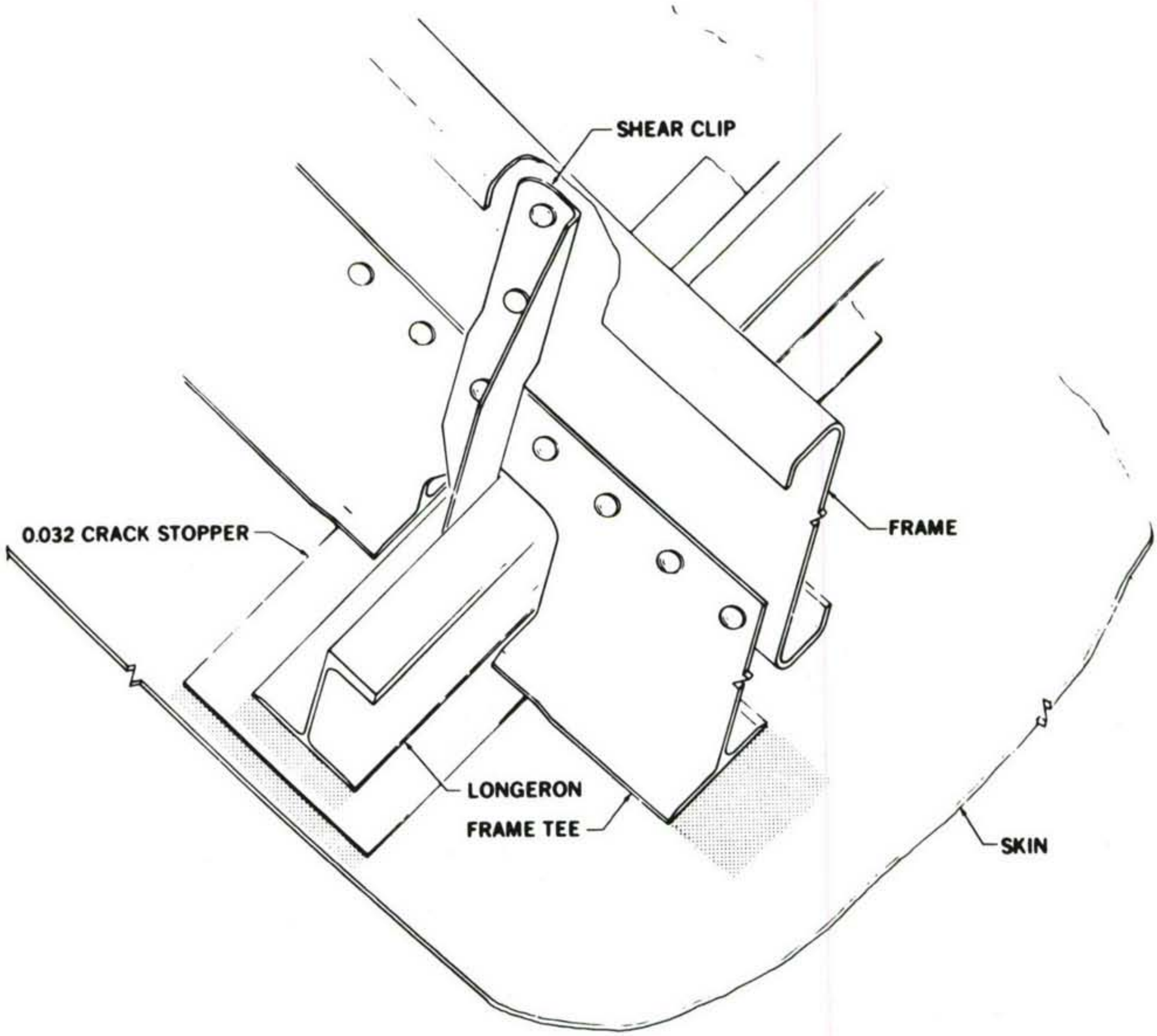


FIGURE 18. FRAME/LONGERON INTERSECTION

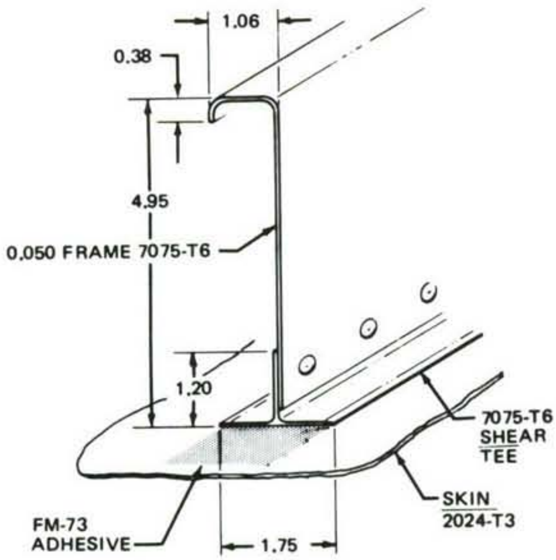


FIGURE 19-a. TYPICAL BONDED NOSE FRAME INTERSECTIONS

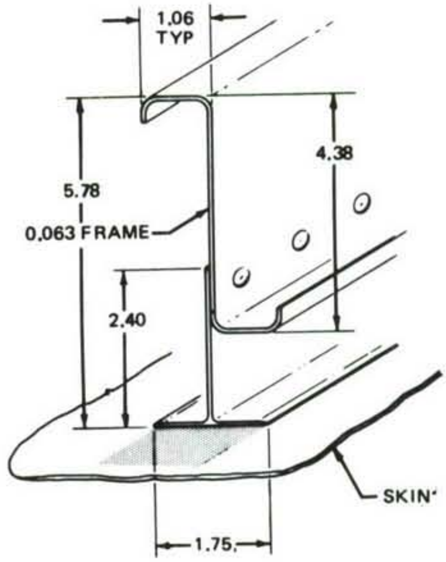
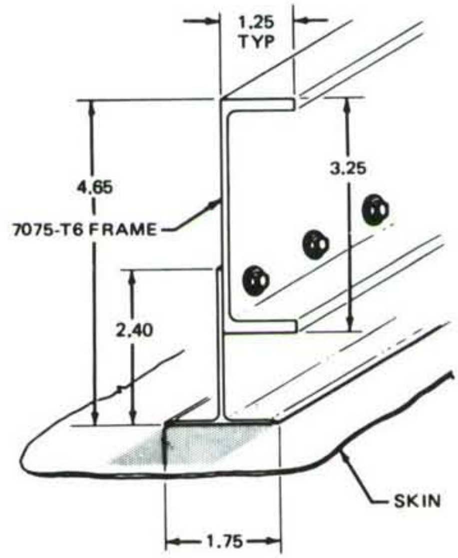


FIGURE 19-b. TYPICAL BONDED CONSTANT SECTION INTERSECTIONS (STA 463, 487, AND 511)



NOTE: MATERIALS SHOWN FOR NOSE SECTION ARE TYPICAL

FIGURE 19-c. TYPICAL BONDED FLOOR SUPPORT BULKHEAD INTERSECTIONS

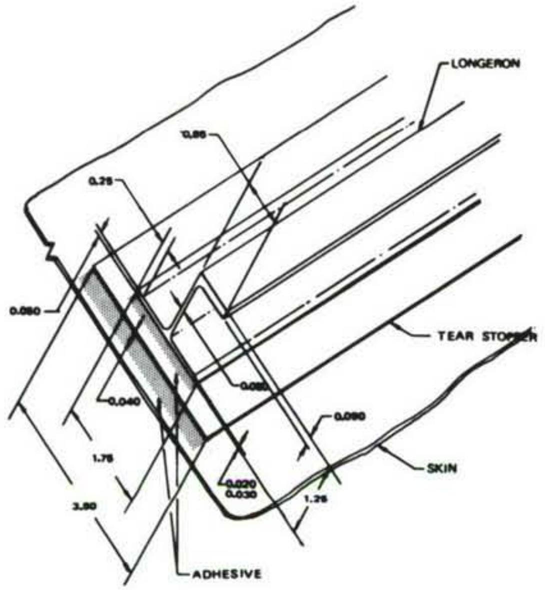


FIGURE 20-a. TYPICAL BONDED LONGERONS 2 THROUGH 7

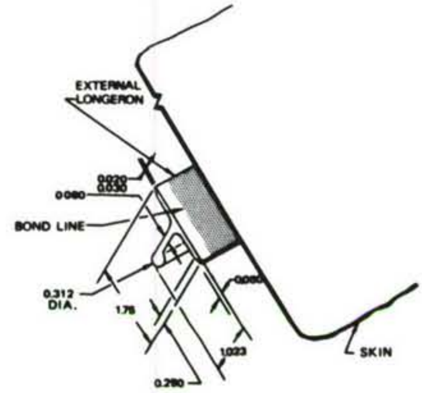


FIGURE 20-b. TYPICAL BONDED LONGERONS 11, 12, 14, 15, 16

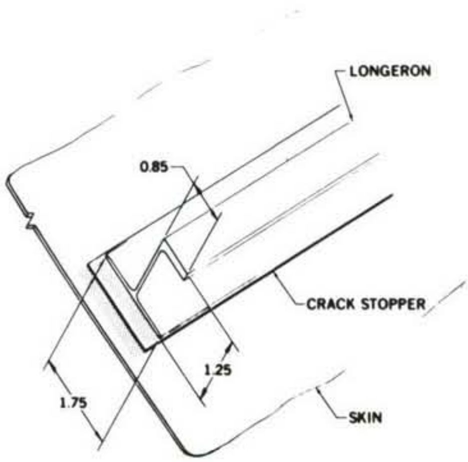


FIGURE 20-c. TYPICAL INTERNAL LONGERON

SECTION III
TECHNICAL DISCUSSION

3.1 HISTORY OF BONDING TOOL DEVELOPMENT FOR PABST

The original tooling concept of a female bonding tool was selected on the basis of program schedule prior to the engineering definition of the structure. In order to compress the schedule, it was decided to construct the tool concurrently with the design of the structure. At that stage, only the outer contour of the structure was known and, since three concepts were to be manufactured and tested as large panels, it was felt that one universal female bonding tool was the right way to proceed. The honeycomb concept had not been eliminated at that stage, and it was intended that the single large tool be used to make test panels of various lengths. Therefore a continuous surface tool was fabricated.

Two prime problems were encountered in the use of this female bonding tool. The first problem was that the frame shear tees were so stiff that their contour mismatch and local waviness were such that they would not deflect to fit the inside of the skin, in order to provide reasonably uniform bond lines. Some test panels contained external doublers for load introduction and splicing. Consequently, the primary skin was lifted off the tool surface by spacers, which meant that the skin radius was less than that to which the shear tees had been stretched. Thus, because of the existence of varying thicknesses of external doublers, the concept of a universal female tool was shown to be invalid. Subsequently, during Phases IB and II, the shear tees were extensively reworked and hand scraped to try and improve the fit. This was a laborious procedure which obviously could not be tolerated for production where man hours must be kept to a minimum. Even with this hand work, multiple layers of adhesive film were needed and as a result glueline thicknesses varied from 0.002 inch to 0.026 inch.

Since one important purpose of adhesive bonds is to transfer loads evenly between metal elements of bonded joints, the bond must produce uniform strength along the length of the joint. Ideally, this requires that the thickness of the adhesive layer be maintained essentially constant, thus

eliminating formation of the thin bonded areas which are stiffer and would attract more than their share of the load from adjacent thick and softer bonds. One should no more use a variable thickness adhesive layer to absorb tolerances in the metal details than permit a random mixture of fastener diameters in a mechanical joint.

The next major problem involved the use of 1/4 inch hollow aluminum beads, Figure 21, to cover the inside of the skin up to the height of the shear tees (about two inches) in an attempt to simplify the bagging operation and reduce the likelihood of a bag failure due to puncturing by a sharp cornered detail. Occasionally in practice, the "beads" locked up solid in the vaccuum bag and actually prevented the uniform transmission of the autoclave pressure to the bonding surfaces, as shown in the upper view of Figure 22.

In an attempt to alleviate this problem, pressure plates were incorporated into the layup, as shown in the lower view of Figure 22.

FIGURE 21. APPLICATION OF HOLLOW ALUMINUM BEADS TO THE FEMALE BOND TOOL

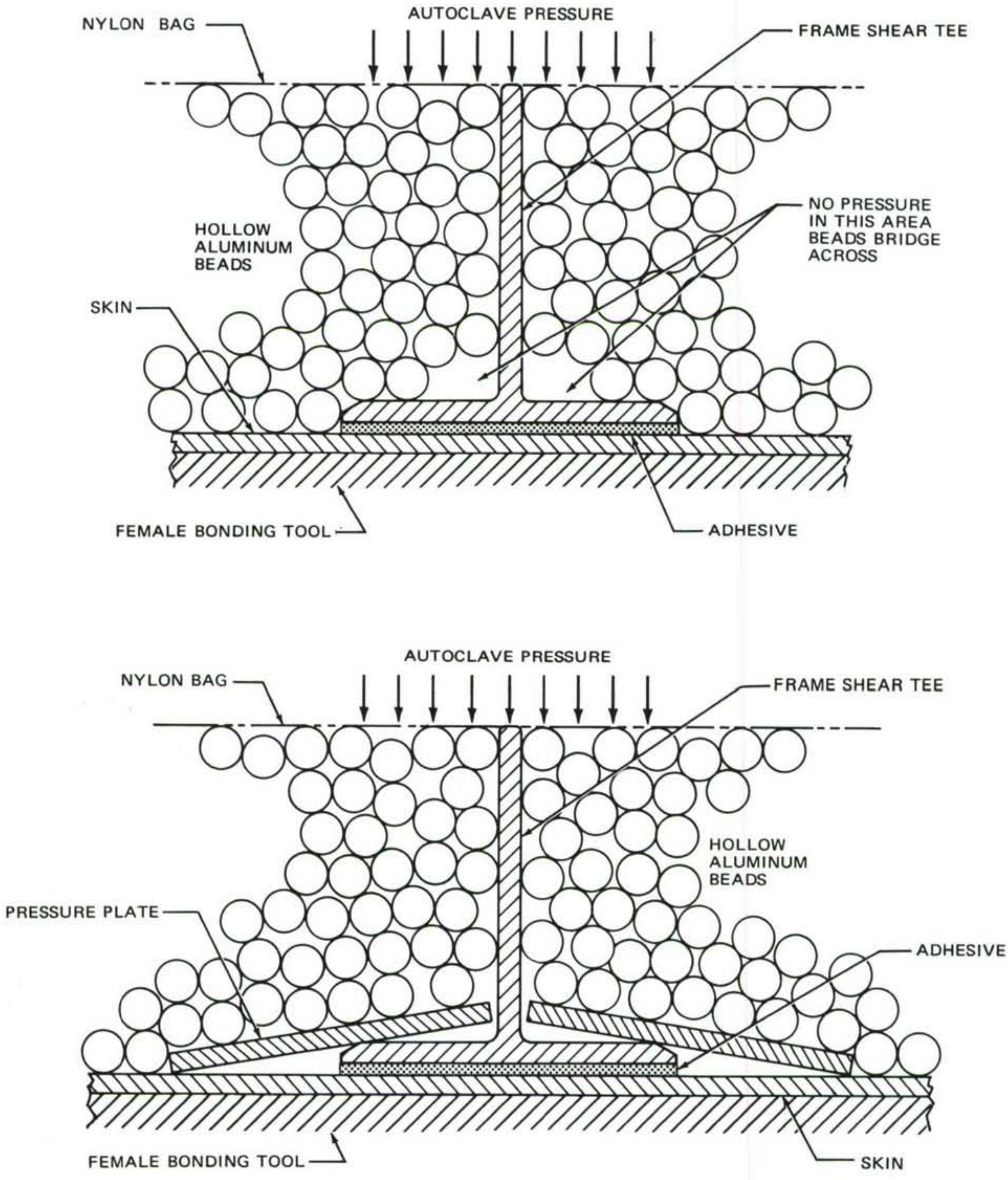


FIGURE 22. PROBLEMS USING HOLLOW ALUMINUM BEADS WITH THE FEMALE BOND TOOL

However, problems still remained in obtaining equal pressure on the inside and outside of the longerons and shear tees where they crossed, because of the overhanging of the longeron inner flange. The difficulties in ensuring equal pressure on both sides of the parts, when bagging against the female tool, were aggravated whenever there were external skin doublers or splice plates in the assembly to be bonded.

It was becoming ever clearer that, instead of trying to force the stiffeners to match the skin contour, such as was required by the female tool, it would be much better to support the stiffeners and push the thin, flexible skin up against the stiffeners. That this would in fact work was verified by envelope bagging an assembly and resting it in the female bonding tool as a cradle. Figure 23 shows the dramatic improvements in the quality of skin/stiffener bond joints on a typical envelope bagged panel. The large area of disbonds typically encountered with panels made using the female tooling concept are shown in Figure 24. Notice that the envelope bagged panel has achieved almost total bonding in stiffener backed areas.

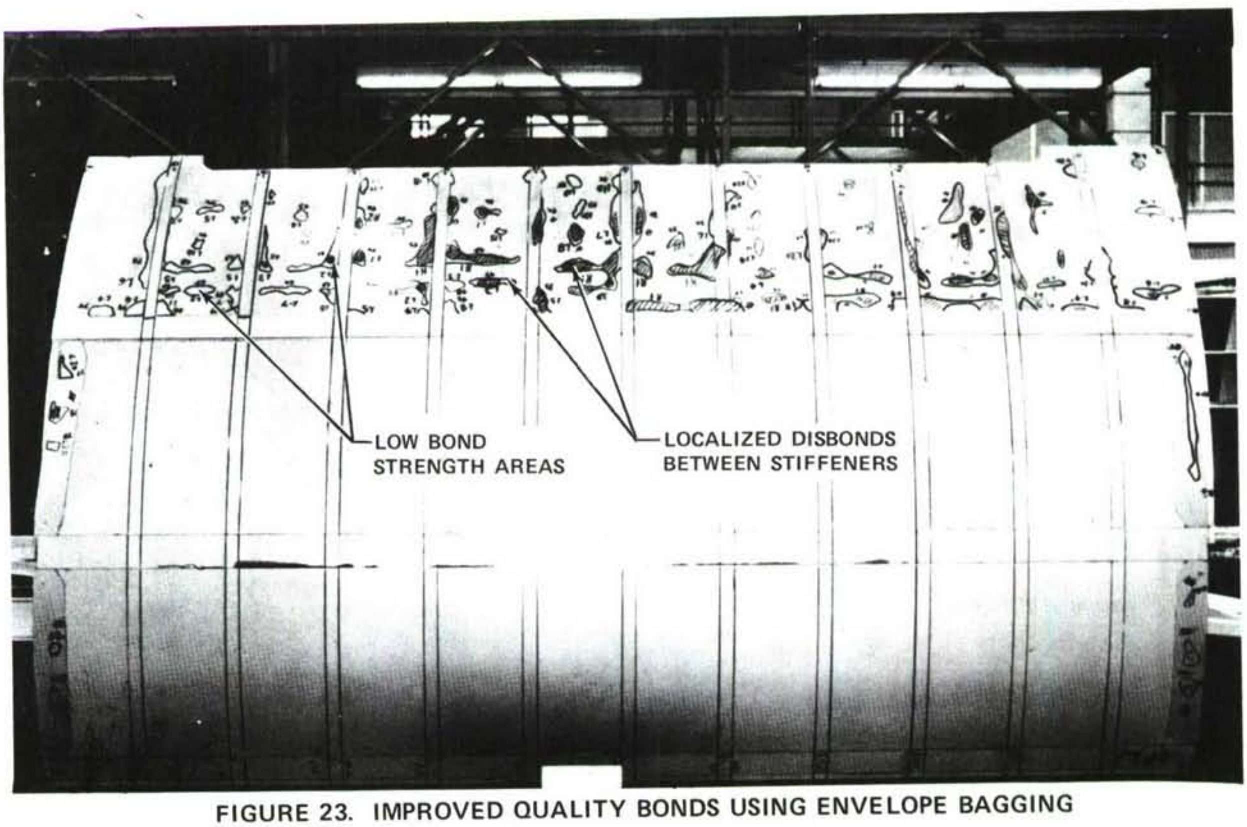


FIGURE 23. IMPROVED QUALITY BONDS USING ENVELOPE BAGGING

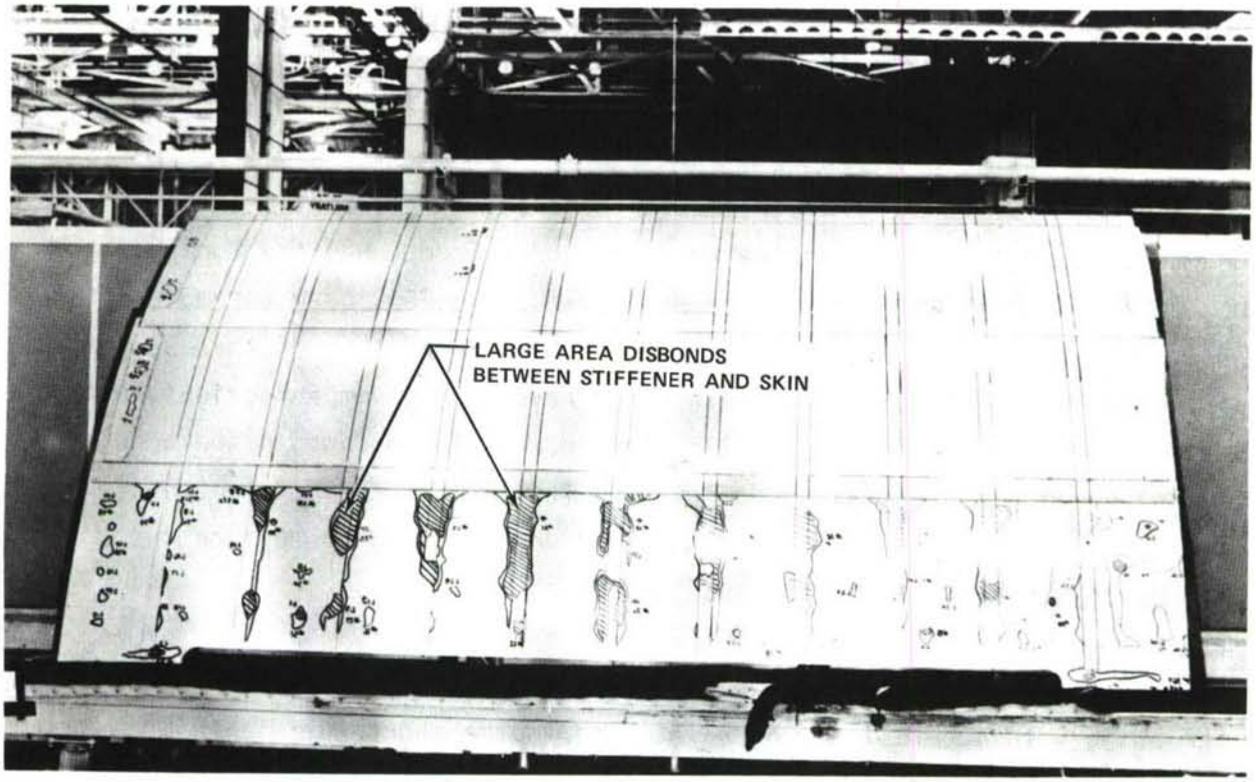


FIGURE 24. TYPICAL QUALITY BONDS USING THE FEMALE TOOL

It had been recognized at the start of the program that a female bonding tool would be quite impractical for the compound curved nose section because the stretch-formed skins would not match the tool contour well enough. Wherever the skin fell inside the loft surface locally, it would lift the shear tees off the skin in adjacent areas. On the other hand, where the skin tried to protrude outside the loft surface locally, it would oil-can inwards and form a dimple or a halo in that area, as it contacted the bonding tool. Again the stiffeners located at or near such an area would not fit properly. Because of such considerations and the demonstrated problems with the constant section female bonding tool, the need to use male tooling was recognized, unfortunately, due to compressed schedules both male and female bond tools were utilized.

The switch in tooling concept provided a major improvement in quality of the bond. While the fabrication and bonding experience with the male tool made it very clear that the male tool approach was preferred for adhesive bonding, the switch occurred late enough in the program that not all of the problems were solved prior to fabricating some panels for the FSDC. In

reality, the test results with these poorly fitted panels proved an unqualified success from the standpoint of structural integrity even though each panel had several bondline defects.

Near-perfect panels are anticipated for production, now that the tooling and manufacturing techniques are properly understood. Had the tooling and other bonding problems been solved earlier and the FSDC been assembled from perfect bonded panels, there would have been no resolution of the question as to how sensitive the test result would have been to imperfections in the bonds. It is appropriate to outline the known deficiencies in the bonding technique and the cures which are planned for them in the future because most such improvements would be associated with reduced production costs as well as an improvement in bond quality.

The problems associated with the male bonding tools for PABST are largely attributable to scheduling constraints and to the short cuts taken because so few panels were to be built with no two precisely alike.

The basic male tool concept is again shown in Figure 25, and consists of a picture-frame tool around the perimeter with contour boards to support each shear tee. The contour boards are notched to let the various longerons pass through. The contour boards were not made specifically for each panel - universal ones were made with wide gaps at each intersection and most of the gaps were filled with custom-sized blocks of plywood, both to prevent the nylon bag from being punctured and also to support the shear tees.

Problems encountered with the male bond tool resulted from difficulties with the envelope bagging, particularly with the bag on the inner side. Due to the deep pockets formed by the intersecting contour boards, it was not possible to shape a bag from the large flat nylon sheet which fitted all the details perfectly without bridging. These problems would not arise in production because either a molded rubber bag or a metal structure would be used to support all of the stiffeners continuously, possibly bonding all of the stiffeners to the skin in one operation. Alternatively, one could simplify such tooling by using multi-stage bonding. The mechanism that caused mark-off on the FSDC skin when using envelope bagging was simply due

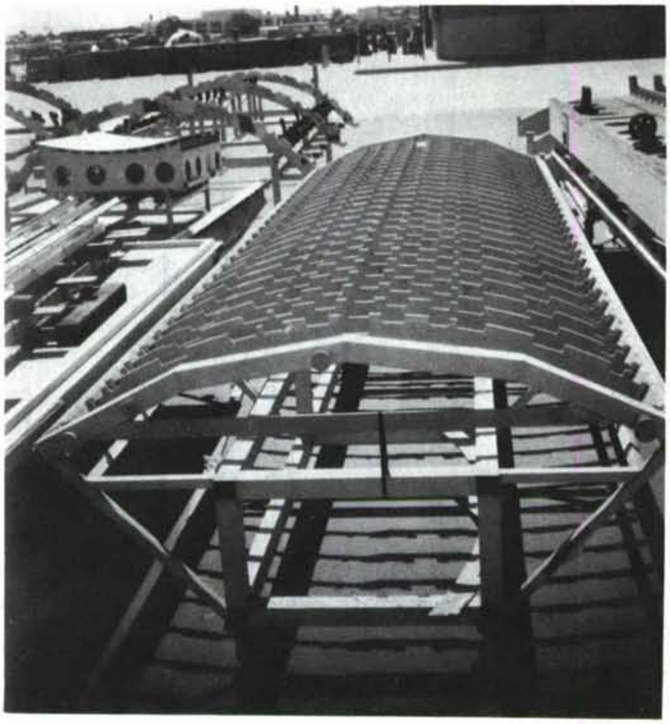


FIGURE 25-a. CONSTANT SECTION MALE BOND TOOL

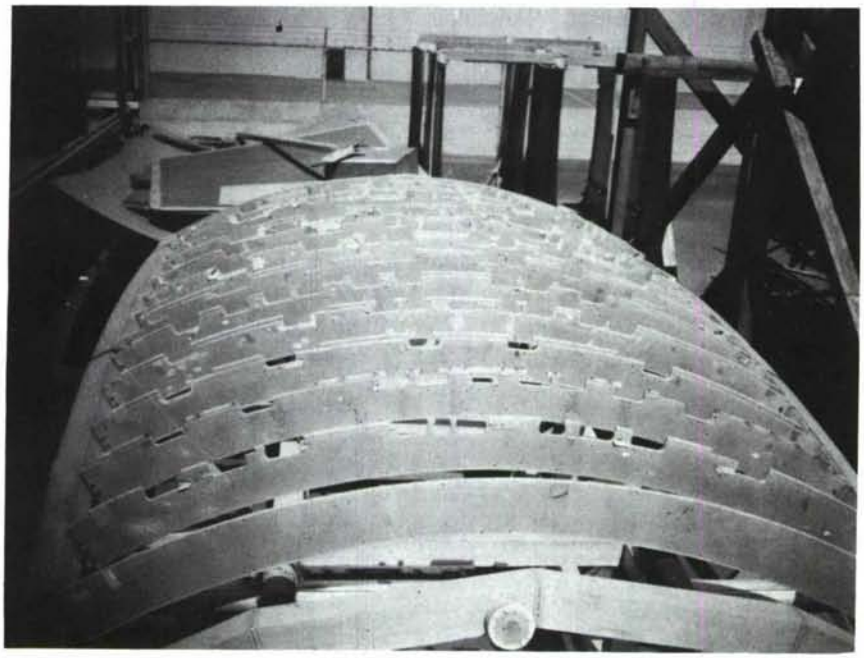


FIGURE 25-b. NONCONSTANT SECTION MALE BOND TOOL

to an imbalance between the areas pressurized on each side of a skin bay. This differential pressure was caused by the use of excessive amounts of bleeder cloth piled in corners of frame shear tees to prevent tearing of the vacuum bag material. This is illustrated by Figures 26 and 27.

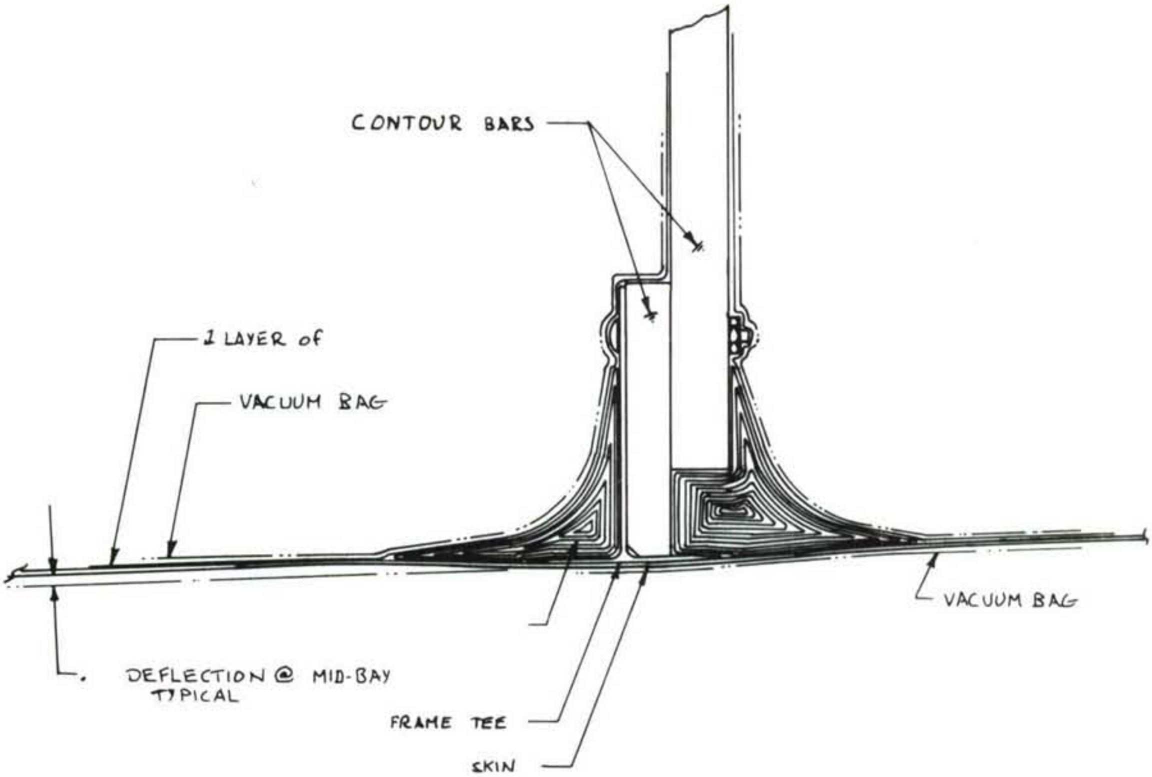


FIGURE 26. POLYESTER MAT TEST

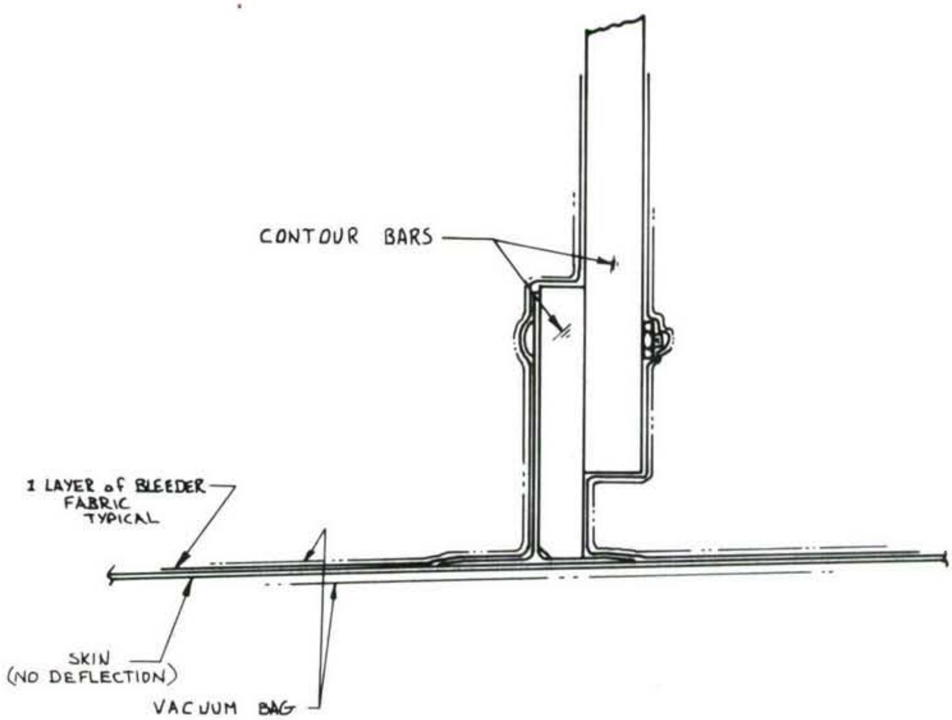


FIGURE 27. ONE LAYER OF GLASS FABRIC BLEEDER

Actually, the problem was manifest in more than one form. Naturally, the bagging problems were even more severe in the corners where stiffeners intersected. Consequently, when longerons were permitted to float while the frame shear tees were tied radially to the contour boards, there were corresponding problems of mark-off between the frame and the longerons as well as between the skin and the stiffeners. In a true male tool, as distinct from an envelope bag tool, this problem could not arise because the intersecting stiffeners would be 100% supported and not free to float. The lesson to be learned from these experiences is that envelope bagging requires a proper molded and contoured bag for complex stiffener layups. Simple bagging with nylon film should usually be restricted to simple layups of skin and doublers. Non-intersecting longitudinal stiffeners in single curvature panels can be successfully envelope bagged without bleeder material which relies on the lack of pockets to drape the bag around the stiffeners thereby minimizing creases, Figure 28. Later exploratory work on PABST has shown this to be quite practical, and this technique has been used in production by Fokker - VFW. What was accomplished during PABST in this regard is that progressively less bleeder material was used on later

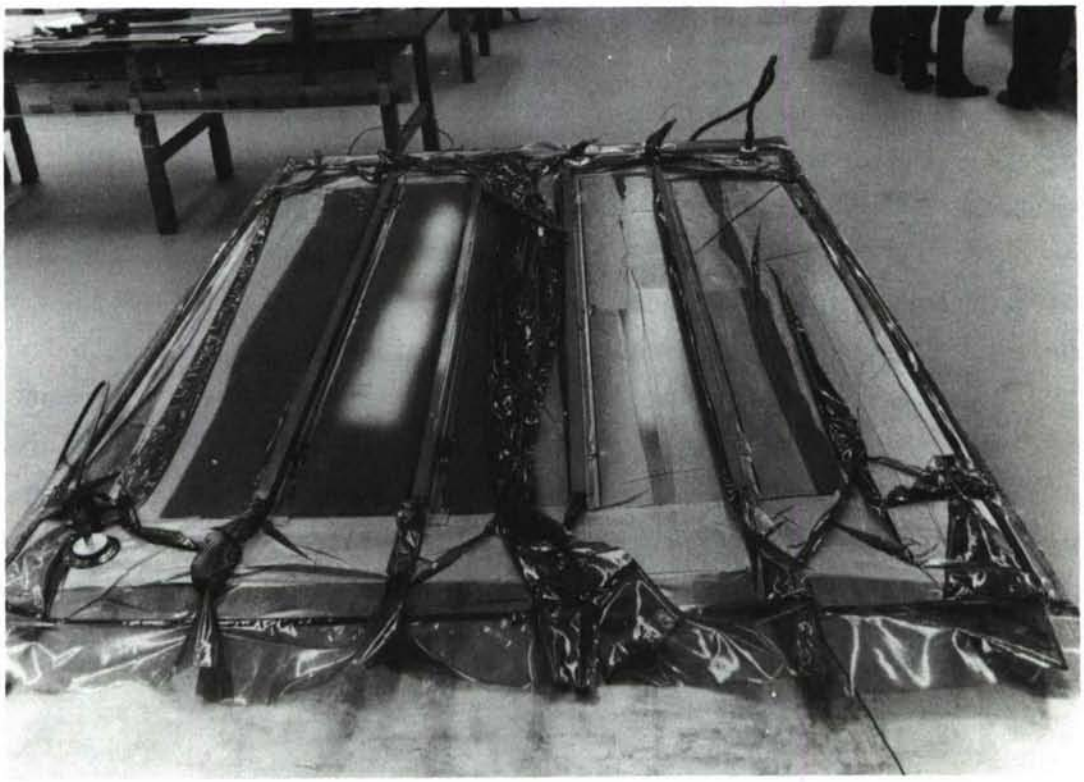


FIGURE 28. ENVELOPE BAG WITHOUT BLEEDER MATERIAL

panels and correspondingly more care was taken in the installation of the nylon bag to prevent puncturing; this led to a markedly reduced and acceptable mark-off.

A further problem associated with the envelope bagging was that the frame contour boards were not locked in position in the longitudinal direction; they were just locked at their ends. The reason for letting them float everywhere else in the longitudinal direction was that it was believed that any intersecting support members would cause deep pockets in the inner bag and thus create bagging problems. The longerons were used to hold the contour boards on station, initially. Finally a much stiffer member was added dcwn the middle of the nonconstant tool to limit the tendency of the boards to move off station due to the differential pressure loads. This proved to be effective.

The basic open construction of the male tool proved to be a very significant advantage because it's heat up rate was much faster than for the female tool. The male tool has a much lower heat sink value since it does not require the rubber blanket on the outside and the aluminum beads on the inside as used on the female tool.

There is no doubt that a production contract for bonded fuselages would use bonding tools based on the principle of supporting the stiff details, such as frames and longerons, and use pressure to push the flexible details, such as skins and doublers, to fit. It is also probable that, since only about 10% of the skin area is bonded, local application of a flexible pressurized tube over the stiffeners may be preferable to a complete pressure bag which would require a back up reaction over the entire inner surface. Other suggested changes would be to bond more of the structure and eliminate further rivets using two-stage bonding, and to develop an automatic inspection system for checking the adhesive bondlines. While general trends of further developments can be identified, it is premature at this time to conjecture upon specifically how these goals would be attained.

3.2 DETAIL TOLERANCE REQUIREMENTS

One of the important lessons learned during PABST was that the detail part tolerances for bonding need be no tighter than for mechanical attachment, Figure 29; providing that the bonding tool is suitable. The tolerance requirements for primary and secondary bonded structures are the same. In bonding primary structures, the tolerances can be harder to hold due to the size and gage of the details, unless the bonding tool is designed to let flexible details deflect under pressure to fit against supported stiff details. If the details can be pressed together with a finger pressure of approximately 5 psi in the bonding tool, then they are suitable for bonding under autoclave pressure. No closer tolerances are required. When two or more stiff details are bonded together, or a stiff detail is bonded in a female tool, stringent tolerances must be applied to minimize the variations in the bondline. Even so, the best that was accomplished on PABST with the female bonding tool still required filling the gaps, as identified by verifilm, with extra layers of adhesive to minimize voids and porosity.

The tolerances were relaxed after testing in Phases 1B and II confirmed that the bondline need be maintained accurately only in those local areas of high load transfer. Much greater variability of bondline thickness and flaws could be tolerated in the large areas of low load transfer as shown in Figure 30.

Local tolerances on the base legs of a longeron or a frame tee will affect the adhesive stresses in bonded panels. Compression, shear and pressure loads (peel stresses) in the adhesive between the stiffener and the skin are represented schematically in Figure 31 for several stiffener base leg tolerance situations. Frame tee No. 1 one has a flat faying surface which produces a uniform bondline. The peak stresses appear at the edge of the base. If the tee is extruded with the base slightly concave (frame tee No. 2) the bondline at the edge will be thinner and stiffer and, as a result, the peak peel stresses at the edge of the base will be increased. If the concavity appears locally at the center of the base where there is little load transfer, and the rest of the base is flat, then there is little

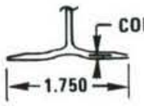
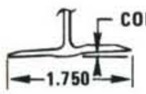
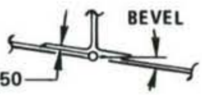
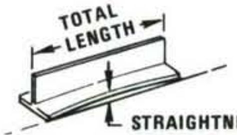
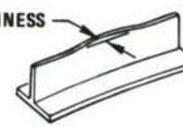
SHEET MATERIAL	DIMENSION AND/OR CONFORMITY TO CONTOUR	BOND DETAIL	MECHANICALLY FASTENED	COMPARISON
	 108 R CONSTANT SECTION	±3.00 R WITHIN 0.032 IN. OF THE LOFT LINE	WITHIN 0.032 IN. OF THE LOFT LINE	EQUIVALENT
	 649.96 R NON-CONSTANT SECTION	0.047 IN. OF THE LOFT LINE	WITHIN 0.032 IN. OF THE LOFT LINE	LESS STRINGENT FOR BOND DETAILS
EXTRUDED DETAILS	 108.00 R SHEAR TEE	WITHIN 0.032 IN. OF LOFT LINE	WITHIN 0.032 IN. OF THE LOFT LINE	EQUIVALENT
	 CONCAVITY 1.750	0.009 IN./IN FLATNESS TRANSVERSE	0.004 IN./IN FLATNESS TRANSVERSE	LESS STRINGENT FOR BOND DETAILS
	 CONVEXITY 1.750	0.006 IN./IN FLATNESS TRANSVERSE	0.004 IN./IN FLATNESS TRANSVERSE	LESS STRINGENT FOR BOND DETAILS
	 DEGREES TWIST	1/2 DEG MAXIMUM TWIST	APPROXIMATELY 1/2 DEG TWIST	EQUIVALENT
	 BEVEL 0.050	±1 DEG	±1 DEG	EQUIVALENT
	 TOTAL LENGTH STRAIGHTNESS	APPROXIMATELY 0.0125 IN./FT	0.0125 IN./FT	EQUIVALENT
	 WAVINESS	APPROXIMATELY 1/32 IN. AND SHALL FAIR IN NOT LESS THAN 10 IN. OR 0.003 IN./IN. OF LENGTH	1/32 IN. AND SHALL FAIR IN NOT LESS THAN 10 IN. OR 0.003 IN./IN. OF LENGTH	EQUIVALENT

FIGURE 29. TOLERANCES ON BOND DETAILS VERSUS MECHANICALLY FASTENED DETAILS

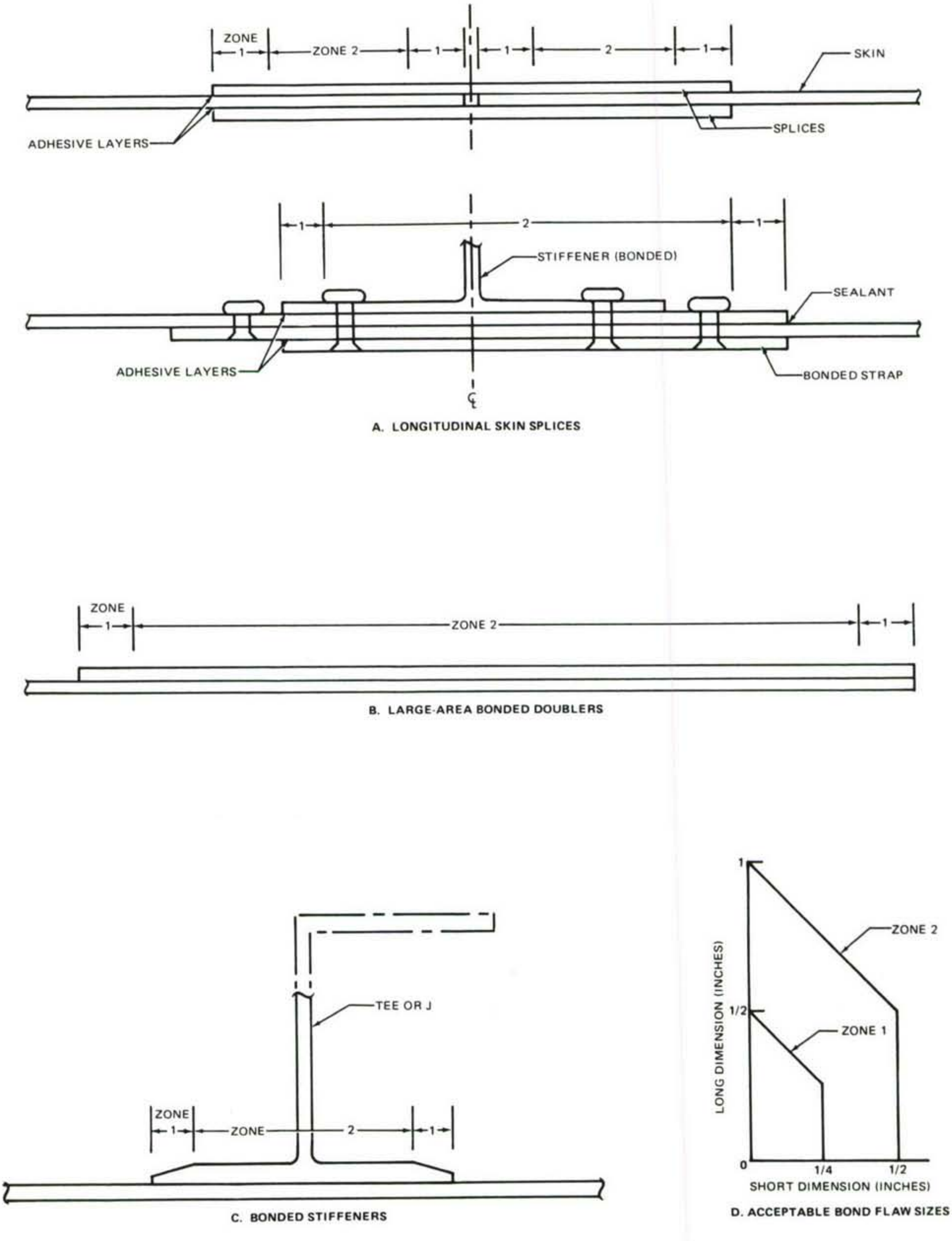


FIGURE 30. TYPICAL QUALITY ZONING FOR PABST BONDED JOINTS

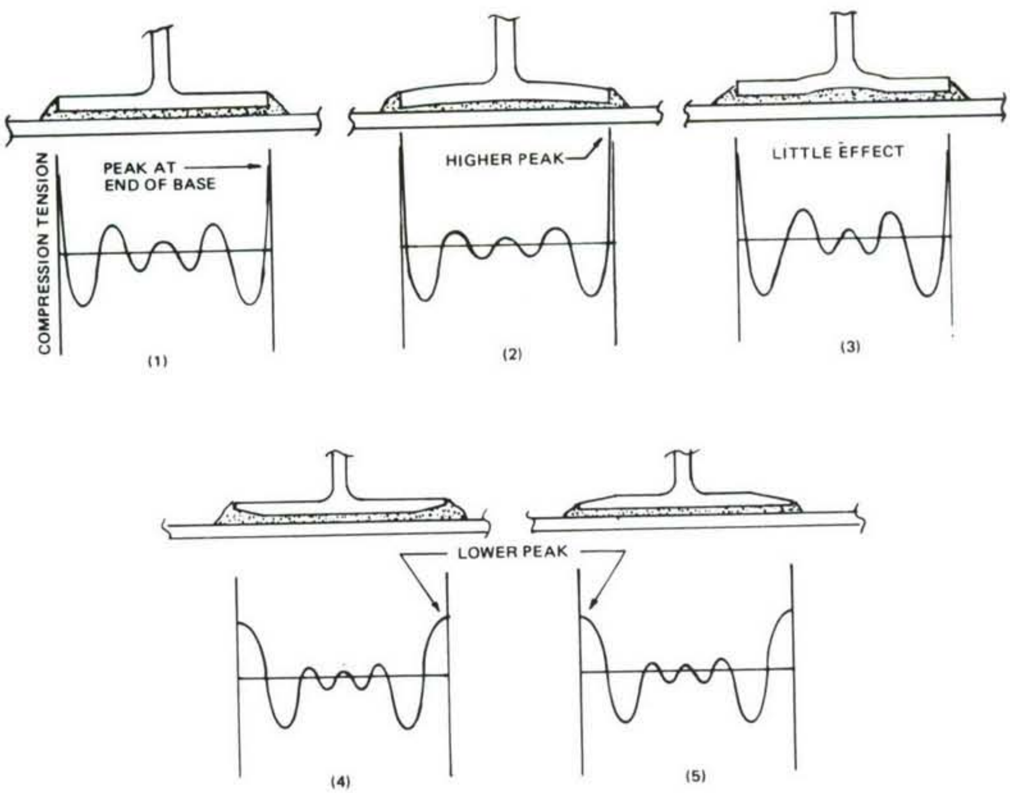


FIGURE 31. EXTRUSIONS AND PEEL STRESS DISTRIBUTIONS

effect on the peel-stress distribution. Frame tees No. 4 and 5 are examples of the strongest joint configuration having the greatest resistance to peel stresses.

The chamfer on the bottom of the base creates a thicker bondline at the edge which lowers the peak peel stress and moves it to the thin bondline area. Frame tee No. 5 affects the peel stress distribution in the same way by making the stiffener base more flexible at the edge.

Since much of the bonded secondary structure involves lesser load transfers than for primary structure, it is evident that industry standards for detail tolerances are, in most cases, much more stringent than justified. Consequently, far more machining of detail parts to achieve precise contours has been practiced than is actually necessary.

When inspecting during the prefit operation, all bonding details should allow for maximum bondline thicknesses of 0.002 inch in metal-to-honeycomb areas, and 0.007 inch in metal-to-metal areas.

Integrated Computer Aided Manufacturing (ICAM) systems have a natural application in both fabrication and assembly of adhesively bonded details; especially in areas where labor and skill intensive operations exist, and where inconsistencies, out-of-tolerance conditions, high cost and low productivity are the rule.

Most formed metals in present airframes are aluminum extrusions with a variety of cross-sections such as Z, T, I, and J. Many of these frames will be stretch-wrap formed to close tolerances repeatedly with an ICAM control system.

The advantages of a computerized NC stretch-wrap forming machine include:

- Elimination of most, if not all, of the post-stretch forming, including traditional checking and straightening.
- Expected elimination of one complete setup and forming cycle, traditionally required by two stage stretch forming.
- Reduced dependence on operator skills.
- Facilitated positioning of parts in the tool.
- Automatic allowance for time-out-of-ice-box for age-hardening details.
- Deleted requirement for templates.
- Improved part uniformity, tolerance and rate of production.
- Quality assurance information available at the tool.

3.3 BONDING TOOL APPROACHES

Figure 32 is provided as reference to clearly show where the various bond tools were used.

A female bond tool, Figure 33, was chosen initially for bonding the FSDC constant section panels. The addition and deletion of contour boards permitted the tooling to be adapted to each panel for the installation and assembly of the shear tees, intercostals, doublers, etc. However, this design limited the methods available for indexing and holding details in order to ensure proper alignment in the joining operation. The female tool is best suited for structures containing light internal members that fit accurately, and where the skin and stiffeners can be pulled to the shape of the tool under autoclave pressure. The shear tees used on the FSDC presented a problem with the use of the female bond tool and usually required excessive amounts of hand scraping or machining during Phases IB and II to provide the close fit of details. A solution to this problem was

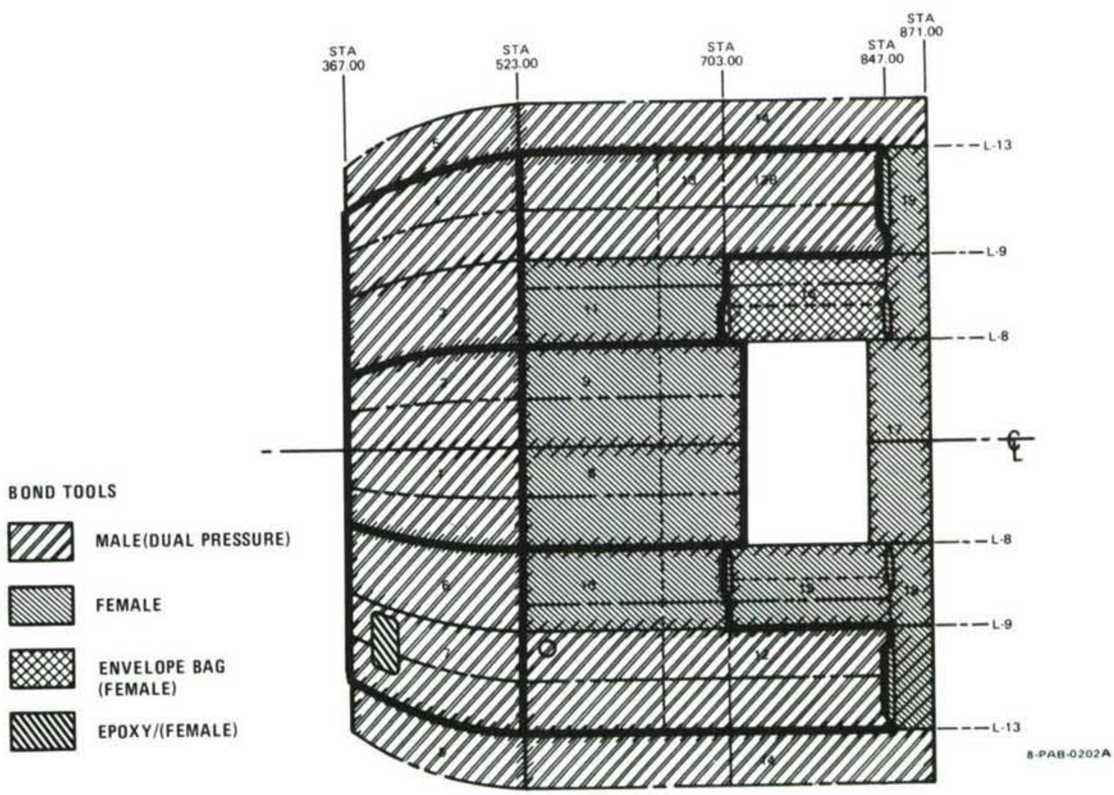


FIGURE 32. BOND TOOLS UTILIZATION

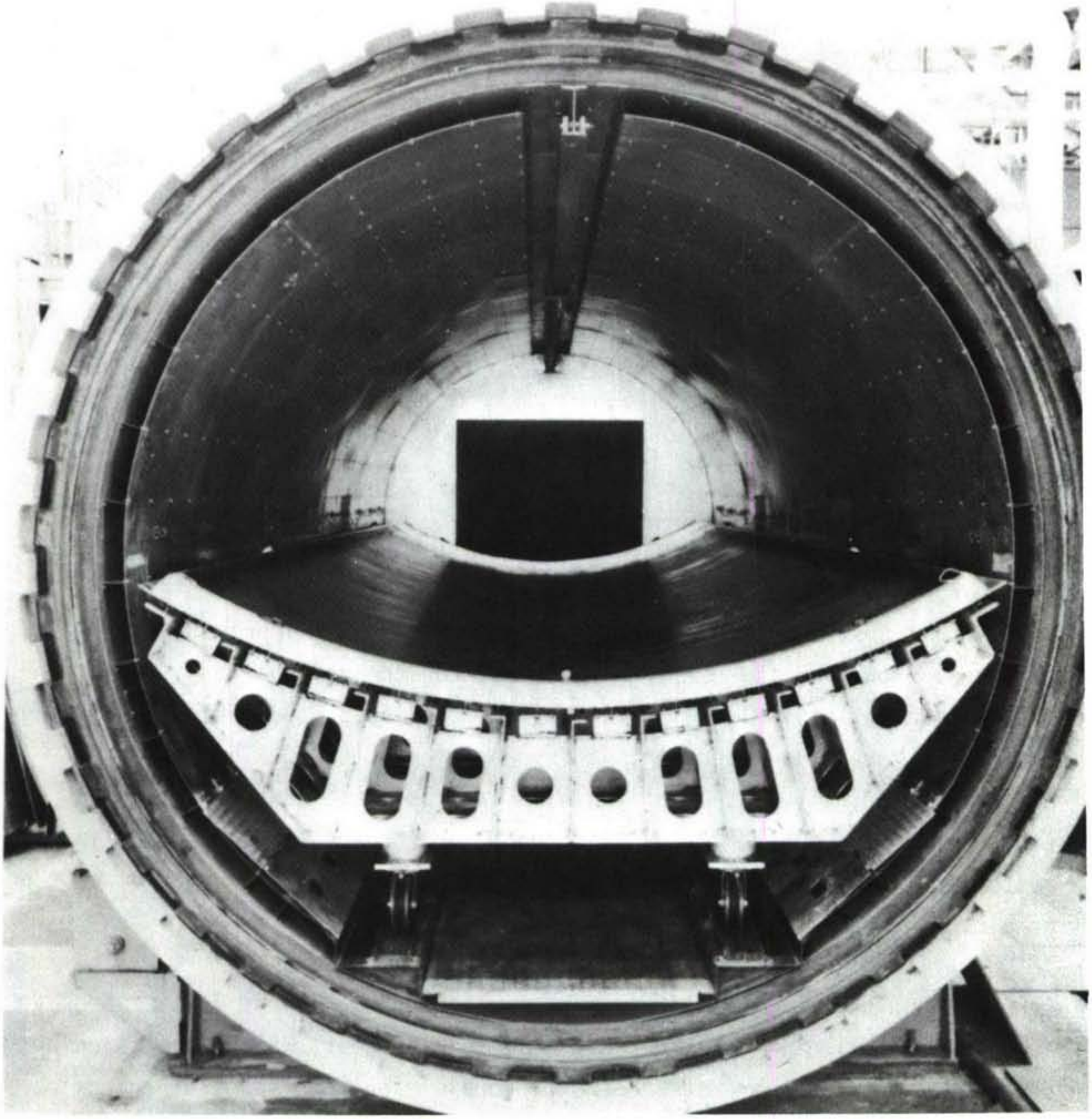


FIGURE 33. CONSTANT SECTION FEMALE BOND TOOL IN THE AUTOCLAVE

found in Phase III by envelope bagging the skin and stiffeners using the female tool as a cradle. The panel UJ797715-402, shown in Figure 23, was the only one fabricated in this manner, but results proved conclusive. Most of the close tolerance requirements and associated detail rework encountered using the female tool were eliminated when the male bond tool was introduced.

The PABST male tool, Figure 34, consisted essentially of a stiff picture frame around the periphery with a series of transverse contour boards at each frame station to locate and support the shear tees on the inside of the assembly. Autoclave pressure was transmitted across the bag on each side of the bonded assembly, so that the skin was free to deflect until it rested on the stiffeners. This tool was much less expensive to build than the female tool. This dual bag tool is the easiest of all bonding tools to use reliably because the skins are accessible from both sides for inspection of fit. The PABST experiences with the male tool were encouraging as the bond quality improved significantly in comparison with female tool bonds in terms of markedly improved verifilms and a reduction in voids and porosity as shown in Figure 35.

The male tool effectively bonded the external longerons on the lower panels of the FSDC which was impossible using the female tool. The male tool is easily cost-justified for production with some bagging improvements required. However, the use of nylon sheet for the internal bag, as on PABST, raised two problems. The first was the large labor effort in laying up the bag carefully to prevent it from being punctured. The second problem, especially on the early panels, was bridging caused by the excessive use of bleeder material to pack the corners which resulted in aesthetically unacceptable mark-off at the stiffeners on the outside of the panels.

Even for low-volume production and/or development work, the least expensive approach overall utilizes the PABST male tool concept, which is particularly suitable where there are stiffeners or doublers on both sides of the skin. However, the reduced initial tooling costs must be balanced against the present difficulty in vacuum bagging on the inside, Figure 36, so this developmental bagging procedure is not recommended for production. Properly formed reusable rubber bags would overcome this bagging problem and further enhance the cost effectiveness of this approach.

FIGURE 34-a. MALE BOND TOOL – SKIN AND EXTERNAL LONGERON

FIGURE 34-b. MALE BOND TOOL – INTERNAL CONTOUR BOARDS

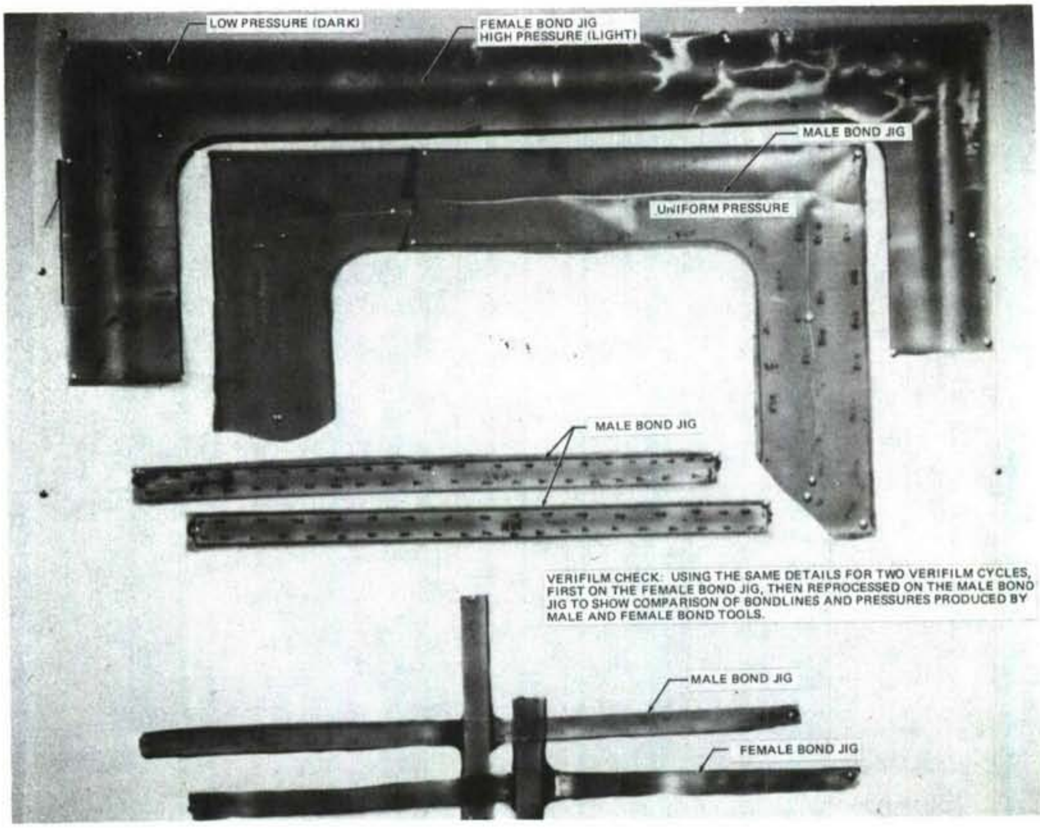


FIGURE 35. COMPARISON OF MALE AND FEMALE BOND TOOL VERIFILMS

FIGURE 36. BAGGING THE MALE BOND TOOL

To summarize the tooling approaches developed during the PABST program; there were two primary bond tool concepts, female and male, which have advantages and disadvantages evaluated as follows:

FEMALE BOND TOOL

Advantages:
- Easier control of outer mold line surface of aircraft.
- Simpler vacuum bagging - one side only.

Disadvantages:
- Very high pressure needed to force details to skin.
- Bondline thickness is highly variable for stiff details.
- More voids in bondline.
- Need closer tolerance and fit of details.
- Slower heat-up rate - greater tool mass.
- Longer cure cycles with greater risk of a "blown bag".
- More movement of details during cure cycle.
- Poor transmission of pressure due to bridging problems with intersecting stiffeners.
- The use of hollow aluminum beads to simplify bagging prevented a uniform transmission of autoclave pressure.
- Impractical for compound curvature bonded assemblies.
- Inaccessible for inspection, during prefit and layup, where doublers are bonded on outer surface and under aluminum beads on the inside.
- Potential of excessive skin mark-off at stiffeners if excessive bleeder material is packed in corners to permit bridging of the inner bag while also preventing it from being punctured.

MALE (DUAL PRESSURE TOOL)

Advantages:
- Simplifies fabrication process for producing compound curvature panels.
- Better control of bondline thickness.
- Skin deflects easily to fit details.
- Fewer voids and less porosity.

- o More relaxed detail tolerances.
- o No movement of details during bond cycle.
- o Better heat-up rate due to open construction.
- o Easily accessible for fit check and inspection.
- o More economical to build.

Disadvantages:

- o More difficulty in vacuum bagging the internal side using developmental bagging methods due to the contour boards which support the frame shear tees.
- o Potential of excessive skin mark-off at stiffeners if excessive bleeder material is packed in corners to permit bridging of the inner bag while also preventing it from being punctured.

3.4 BAGGING APPROACHES

Bagging is a critical process in secondary and primary structural bonding. Improper technique has been the leading cause of scrapped bonded assemblies.

Several bagging methods were tried during the PABST Program including one-side bagging (female tool), envelope bagging (female tool), and envelope bagging (male dual pressure tool).

When designing bonding tools, the bagging task should definitely be considered in the basic design of the tool.

For vacuum bagging, a single sheet of bagging film is placed over the assembly that is to be bonded. This would appear to be a very simple process, yet it becomes a major bagging problem wherever the assembly has deep pockets and/or heavy stiffener members. The major constraint is the ability of the bagging film to withstand the autoclave pressures and temperatures, and display good elongation properties during the bond cycle. The massive female tool requires the bagging film to withstand an extended cure cycle in the autoclave without breaking down (known as a "blown bag"). It is virtually impossible to get a vacuum bag to fit down into deep pockets without creating bridges, etc.

Double bagging required two separate applications of back-to-back vacuum bags instead of one to provide insurance against the possibility of a leak or a 'blown bag'. In theory, either bag could develop a leak and the other bag would then maintain the seal, but it is not considered a cost effective alternative for production.

Envelope bagging in the female bond tool can be accomplished by bagging the entire assembly, using an additional vacuum bag placed between the assembly and the tool and sealed to the upper vacuum bag. Such an envelope bag allows autoclave pressure on both sides of the assembly. The pressure on the outside of the skin and the doublers pushes such flexible members tightly against the heavier stiffeners. The disadvantages of envelope bagging in the female bond tool are that the assembly has a tendency to float during the cure cycle, and if there is any type of bridging on the stiffener side, be it due to the bag or the pressure plates or the hollow aluminum beads, this causes severe canning of the soft flexible skin.

Envelope bagging the male dual pressure bond tool is a key process because successful structural bonding depends directly upon the deflection of one or more flexible pieces of structure (like skin) under autoclave pressure to conform to the supported stiff details. Obviously, the best bond can be produced by simply pushing and holding details together from both sides of the assembly. Thus, PABST panels were supported in a picture-frame tool and envelope bagged. A typical bagged constant section panel is shown entering the autoclave on the male bond tool in Figure 37. Figure 38 illustrates the faster heat-up rate made possible by the open construction of the male tool configuration. This provided a very significant cost savings due to increased heat-up and cool down rates which resulted in shorter autoclave cycles.

As stated, there are some difficulties inherent in envelope bagging, but the main problem is keeping the vacuum bag from bridging around the contour support bars. This can be overcome by maximizing the clearance around the details and by using reusable molded rubber vacuum bags. There were two major reasons for most such problems actually experienced on PABST: 1) due to the excess use of bleeder material to pack the corners for protection of

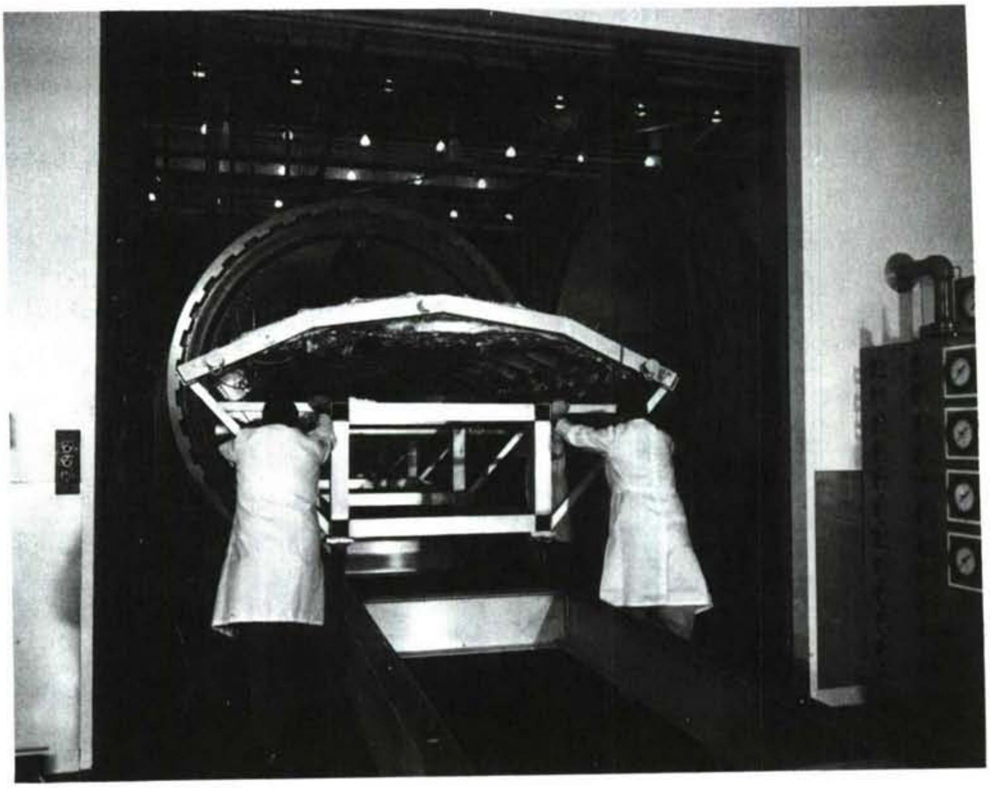


FIGURE 37. BAGGED MALE BOND TOOL ENTERING THE AUTOCLAVE

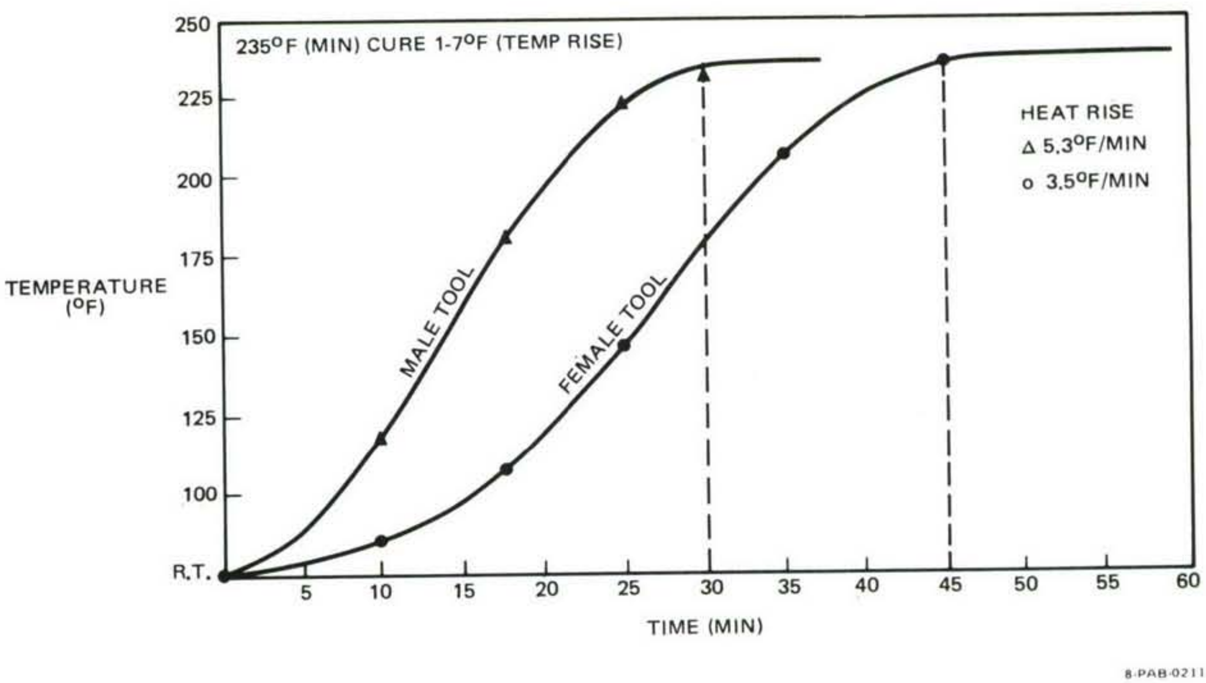


FIGURE 38. TYPICAL TEMPERATURE CURE CYCLES

the nylon bag, and 2) due to the failure to lock both the frame tees and the longerons at the correct radial stations where they crossed.

Compared with the more-costly-to-build female tool, the male dual pressure bond tool is better suited to high production despite the extra effort presently required to bag both sides, since the fit of parts is inherently so much better and both cost and time are saved on the prefit operation and elimination of rework of details. And when applied properly, the envelope bag on a male dual pressure bond tool is the least expensive of any bonding tool, and is capable of producing the highest quality bonded joints and assemblies.

The dual pressure bond tool provides another possibility for further consideration which involves the elimination of vacuum bagging altogether. In theory, the use of local mechanical pressure (as by flexible pressurized tubes) and integrated heaters over the relatively small areas to be bonded can conceivably eliminate present dependence on vacuum bagging and the autoclave. This would significantly change the bonding process and provide a much higher production rate capability.

3.5 PREBOND OPERATIONS

Prebond operations comprise a major portion of the adhesive bonding task. The fabrication of quality adhesive bonded structures depends on careful control of several areas during prebond including:

1) Parts Accountability - A bonded assembly cannot start prefit or bond operations until all detail shortages are cleared. Unlike mechanical assemblies, where one can temporarily bypass a missing detail and later assemble it to the structure by conventional means; in present bonded assemblies one cannot bond if there is even one detail missing.

2) Prefit - This operation consists of fitting the details of the assembly together in the bonding tool prior to the verifilm or bond cycle and thereby provides two essential prebond checks; for detail

part locations and dimensional accuracy. During prefit, Quality Assurance determines the amount and size of gaps between the detail faying surfaces. This was accomplished during the PABST program using a tapered feeler gage in conjunction with five pounds finger pressure. After prefit approval is given by Quality Assurance, each detail is first drilled to provide a means of racking each part during the surface preparation and priming, and then identified with a vibratory pencil, Figure 39, to ensure its re-installation in the same position during the bond operation.

3) Verifilm - This operation satisfied a military specification which required a detail fit-check of the first bonded assembly of each different type. The PABST program was designed to provide data and establish criteria for structural fits and glueline thicknesses, therefore the prefit operation was followed by a verifilm operation. This operation was performed to confirm prefit and provide a prebond record of fits and glueline thicknesses of all details. The verifilm check also provided a means of evaluating the performance of the various tools used in the fabrication of the FSDC panels, reference Figure 35.

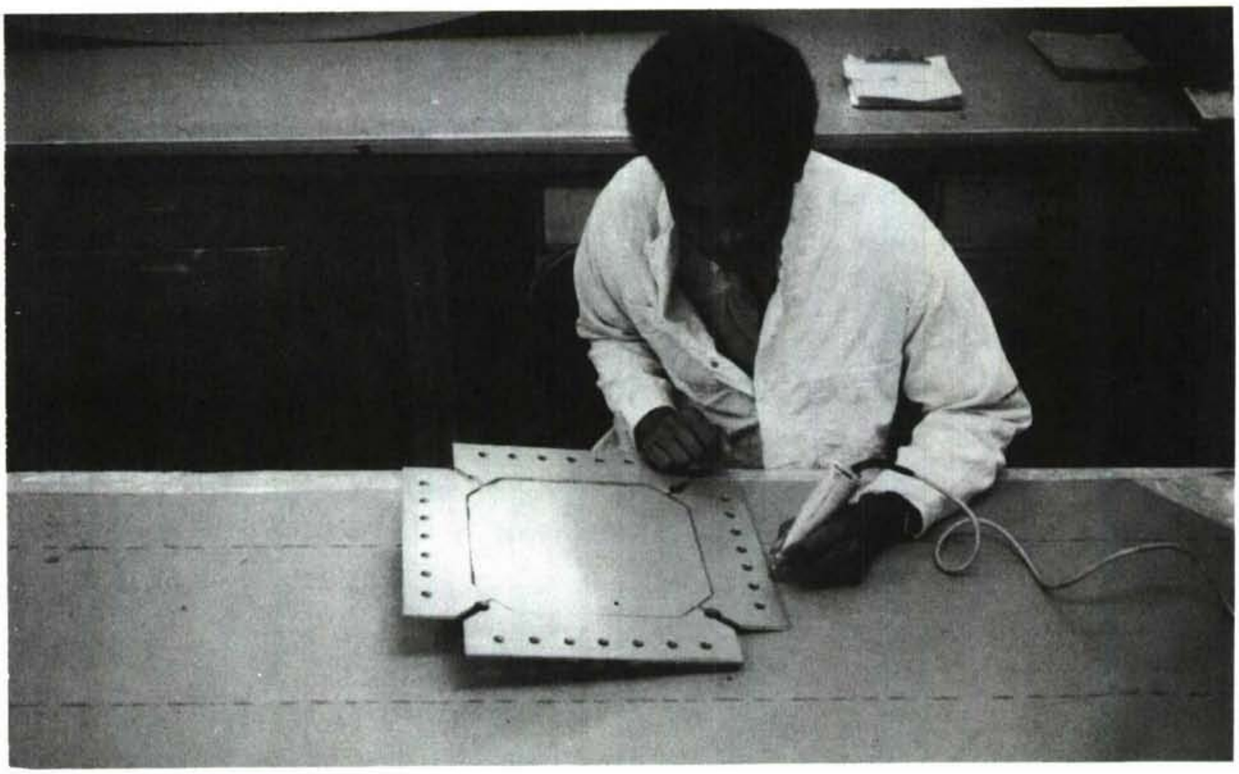


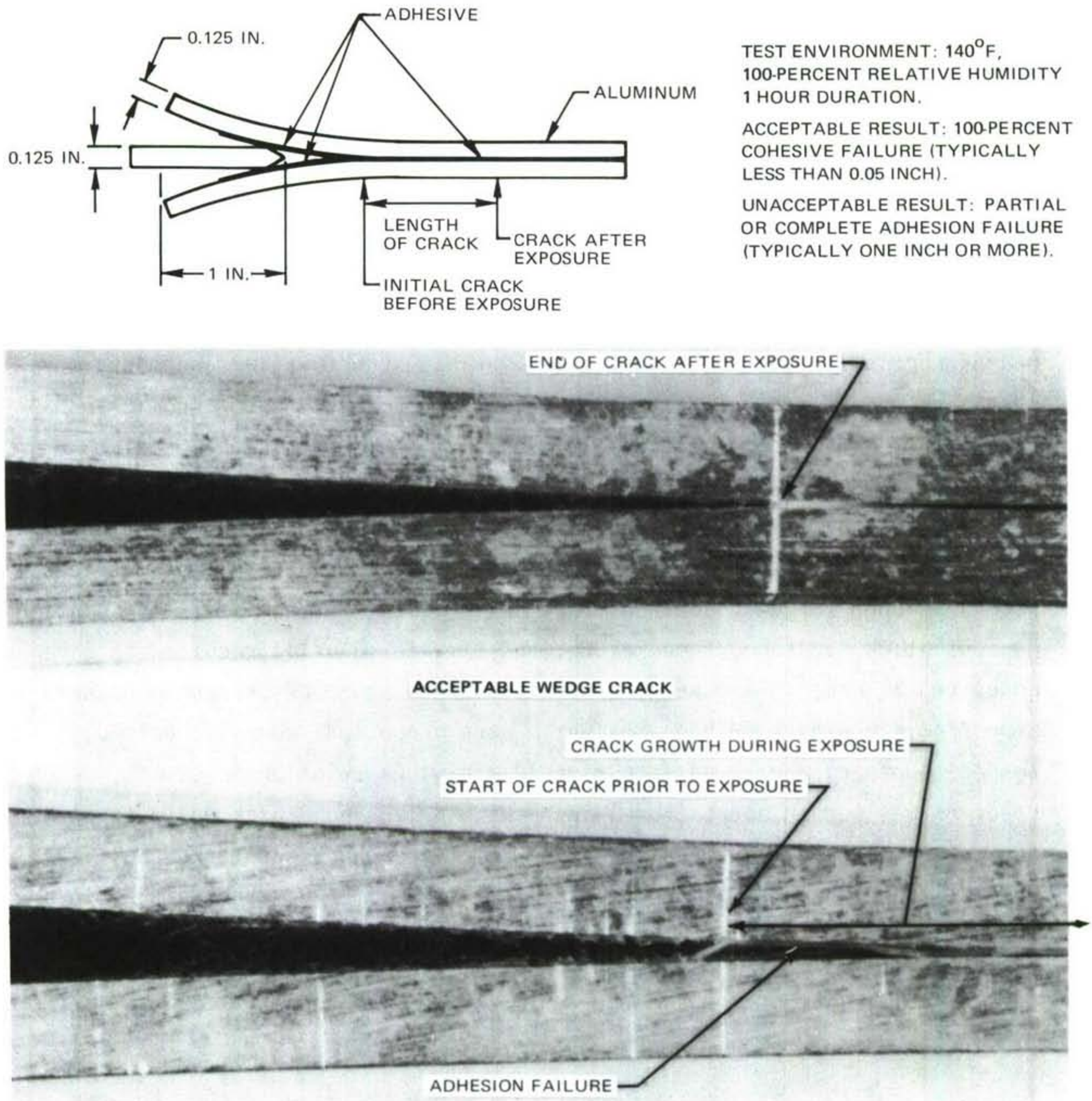
FIGURE 39. VIBRATING PENCIL IDENTIFICATION

American Cyanimid's "Verifilm" was selected for use on PABST panels because it does not bond the parts together and has flow characteristics similar to the adhesive used for bonding. It cures at a low temperature (225°F) in a short time span (20 minutes) and is easily removed for thickness measurements.

3.6 SURFACE PREPARATION

In the first 18 months of the program, many surface treatments, adhesives, nondestructive inspection methods, and various structural arrangements were investigated and many structural tests were performed. Both chromic and phosphoric acid anodize were compared against the sulfuric acid sodium dichromate etch (FPL) surface treatment which was selected to act as a baseline control treatment. The primary test for bond surface treatment durability was the wedge crack propagation test, Figure 40. Test mátrices were developed for each surface treatment to identify the limits of solution concentration, voltage, temperature, and time-in-solution required to give cohesive failures in the wedge crack specimen. Wedge crack specimens were made from two 6-by-6 inch plates which were processed, adhesive primed, bonded together, and sawed into five 1-inch-wide strips or specimens. Each specimen was wedged apart (for 1 inch) with a 1/8-inch thick wedge to place the adhesive locally in tension. The end of the crack was marked initially and after one hour at room temperature. The specimen was then placed in a cabinet at 140°F and 95 to 100 percent relative humidity for one hour; then removed and any crack growth noted. The specimen was then completely separated so the failure mode (cohesive vs. adhesive) could be evaluated.

Regardless of the surface treatments, all processes after anodizing were the same. The adhesive primer, American Cyanimid BR-127, was applied within 2 hours after anodizing. The primer thickness was 0.0001 to 0.0003 inch. It was air dried for 30 minutes minimum and then cured at 235-265°F for 60 minutes. One layer of the FM-73 adhesive, 0.060 pound per square foot, with mat carrier was used. The adhesive was cured in an autoclave at 235-265°F for 90 to 100 minutes at 40$\pm$5 psi. The heat-up rate was kept within the limits of 1-7°F per minute. Autoclave pressure was maintained during cool down until 150°F was reached. The aluminum used for the test specimens was nonclad 7075-T6. Comparative tests of



UNACCEPTABLE WEDGE CRACK

FIGURE 40. WEDGE CRACK TEST METHODS AND CRITERIA

these specimens resulted in the selection of phosphoric acid anodize because no adhesive failures occurred within the full range of this test matrix. Other processes had adhesive failures except when the test matrix conditions were held to close tolerances that were not considered practical in a production environment. To date on the PABST program, over 10,000 phosphoric acid anodized wedge crack specimens have been prepared in a production environment, and all had acceptable cohesive failures when tested.

CAUTION

Experience has demonstrated that all anodized or etched surfaces can be easily contaminated if touched before the primer is applied and cured. Therefore no handling is allowed; not even using white cotton gloves, neutral kraft paper, nor of course, bare hands. During the PABST program, handling was not allowed once the cleaning process started, Figure 41; through anodizing, inspection, and adhesive primer application, and not until the primer was fully cured. Only then were white cotton gloves and neutral kraft paper used to carefully handle and protect parts until unpackaged for the bonding operation.

The phosphoric acid anodizing process sequence, as shown in Figure 42, was implemented into DAC's processing system in June 1975. One 3 x 40 x 12 foot deep tank was converted to a phosphoric acid anodize unit by lining it with lead alloyed with 6 percent antimony.

The phosphoric acid solution became contaminated quickly in production. The contaminants encountered included an aerobic mold similar to the 'mother' found in vinegar; also lead flakes, airborne objects, and insects. Removal of these contaminants was accomplished early in production by adding a filtering system to the tank.

During normal production use of the phosphoric acid anodizing system, a non-uniform appearance called a 'halo effect' occasionally appeared on some of the details. These 'halos' were determined by tests of the base metal to be caused by variations in heat treating, and were not considered degrading to the details.

Titanium wire clips and springs were used to hold the detail parts on dip racks to ensure a proper electrical continuity during the phosphoric acid anodizing process. The use of clips and springs reduced the amount of time required to rack details for the anodizing process by approximately 65 percent, and saved 75 percent in unracking after anodizing when compared with manual tying of details using aluminum wire as done previously.

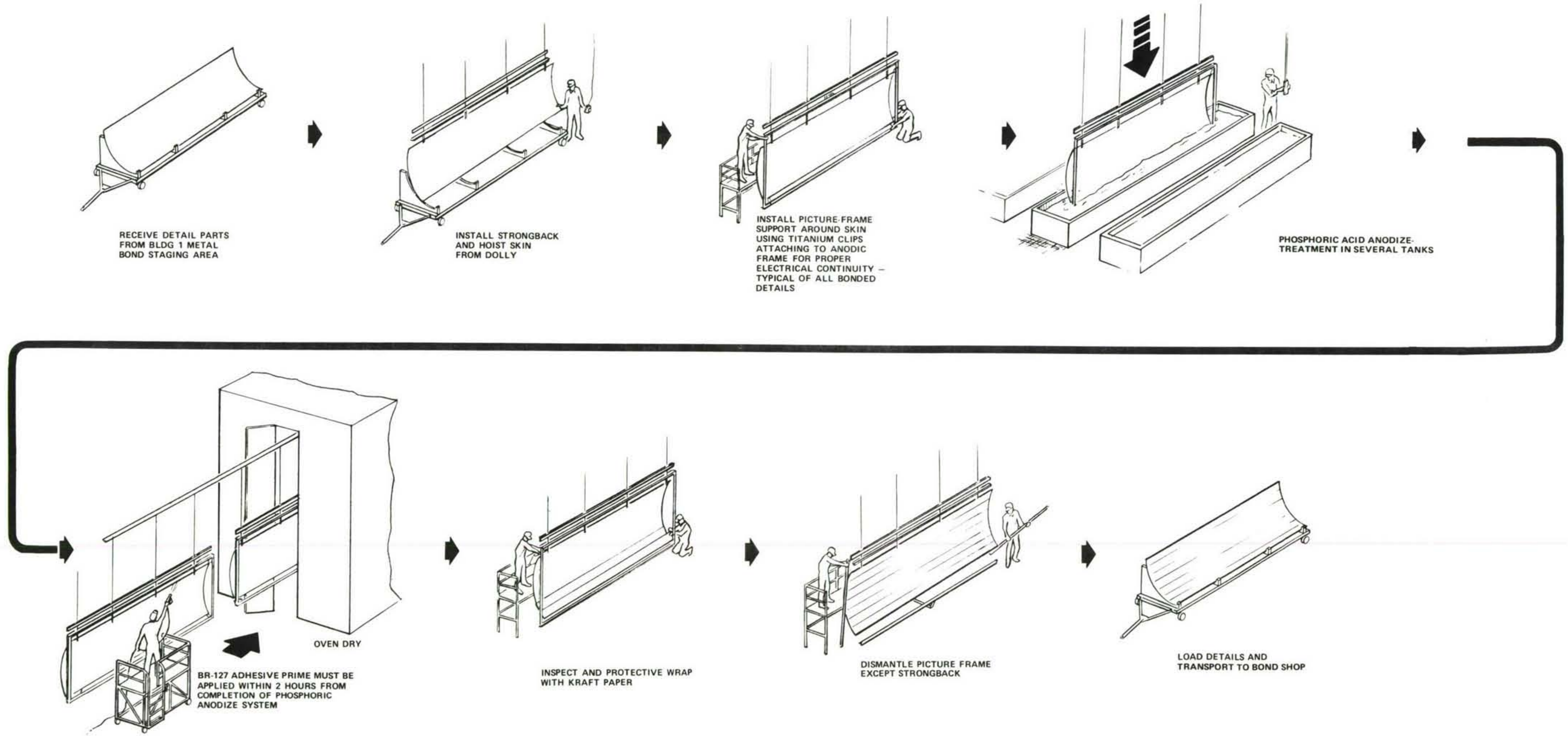


FIGURE 41. MECHANICAL HANDLING OF DETAILS FOR BONDING TO PREVENT SURFACE CONTAMINATION

1	**ALKALINE WASH** 150° ±5°F – 10-15 MINUTES
2	**SPRAY RINSE** COLD DEIONIZED WATER – 2 MINUTES TAP WATER – 2 MINUTES
3	**HOT RINSE** TAP WATER 140° MAX – 5 MINUTES MINIMUM
4	**AMCHEM 6-16 ETCH** AMBIENT – 10-15 MINUTES
5	**TAP WATER RINSE** AMBIENT – 5 MINUTES MINIMUM
6	**SPRAY RINSE** COLD DEIONIZED WATER – 2 MINUTES TAP WATER – 2 MINUTES
7	**PHOSPHORIC ACID ANODIZE** RAISE VOLTAGE IN STEPS TO 10 ±1 V IN 2 MIN MAINTAIN 10 ±1 V FOR 20-25 MIN
8	**TAP WATER RINSE** AMBIENT – 10-15 MINUTES
9	**SPRAY RINSE** COLD DEIONIZED WATER – 2 MINUTES TAP WATER – 2 MINUTES
10	**OVEN** 175° MAXIMUM
11	**TO ADHESIVE PRIME**

FIGURE 42. LAYOUT SEQUENCE OF ANODIZE OPERATION

After phosphoric acid anodizing, the rack of details was inspected with a photographic polarizing filter lens using a mercury vapor fluorescent lamp to illuminate the anodized surface.

In conclusion, it must be re-emphasized that parts must not be touched from completion of surface treatment until primer cure is completed. It is also important to assure good and continuous electrical contact during the anodizing cycle, otherwise poor surface treatment will result. In contrast with the complete lack of contact which is easy to identify, the poor surface treatment associated with intermittent contact is difficult to detect.

3.7 PRIMER APPLICATION

The adhesive primer also plays a major role in the adhesive bonding of primary and secondary aircraft structures by establishing a good interface between the anodic surface treatment and the adhesive. The primer selected, BR-127, contains chromates which protect the surface of the metal details from moisture contamination, corrosion and oxidation. The BR-127 also forms a very good base for corrosion protective coatings outside the bonded areas and helps extend the life of aircraft structural components. A major reason for the use of adhesive primers is that they permit handling of the details between the times of surface treatment and bonding.

During the program, techniques for application and control of the primer and priming operation were developed, Figure 43. It was discovered that the chosen primer's characteristics are such that standard "paint spraying" techniques had to be altered to obtain the desired results. Spraying equipment, Figure 44, was required to agitate and recirculate the primer continuously during the application operation since the chromates included

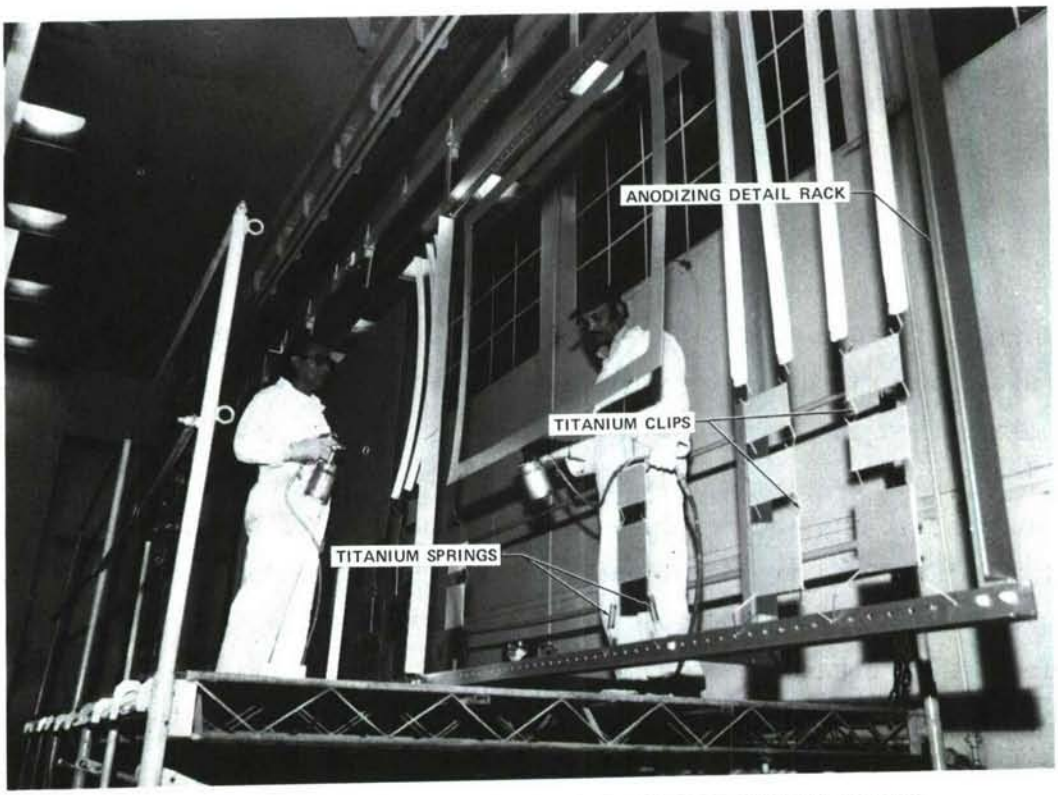


FIGURE 43. TYPICAL PRIMER APPLICATION FOR PABST PANELS

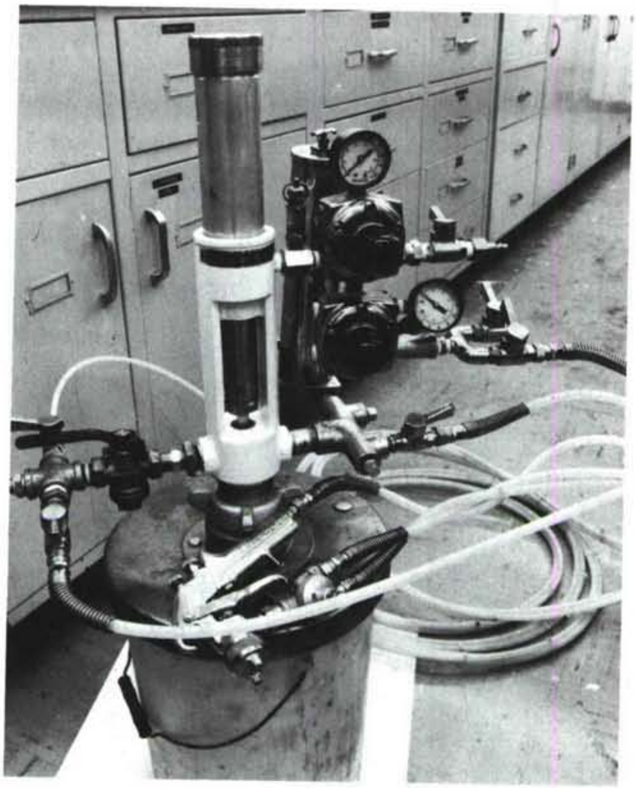


FIGURE 44. ADHESIVE PRIMER SPRAY EQUIPMENT

in the primer had a tendency to rapidly settle out of the solution. The primer has a normal storage temperature of $0^{O}F$ or below. This low storage temperature extends the shelf life of the material to meet normal production requirements. Prior to use, however, the primer must be warmed to room temperature. If the primer were applied cold, excessive moisture condensation would be produced on the primed metal details which would reduce the final product's durability in a hostile environment.

Another variable that must be controlled during the priming operation is the critical thickness requirement. To obtain the best mechanical and corrosion protection, the primer must be applied to a cured thickness of .0001-.0003 inch. This can be difficult to achieve, especially on configured details, and whenever the details are not positioned properly prior to the priming operation. The amount of chromates in the sprayed primer also influences the thickness, since the operator generally relies on the "color" during application for control of thickness. Primer applications that are too thin will not cure properly, can be easily damaged, and can also be removed by common solvents. Primer applied too

heavily will reduce subsequent bond joint mechanical properties by lowering the low temperature shear values. Primer application will not be a problem for trained personnel who utilize the established control procedures.

A promising method for primer application is electro-deposition. This method electrically "plates" the primer onto the metal detail from an aqueous solution. Advantages are several. The primer is a dielectric material and will plate only to a given thickness before the current level dissipates. This ensures a controlled thickness to all surfaces of each detail without regard to detail configuration. Special positioning is not required except for draining. Spray booths and associated equipment are not required and air pollution from solvents is essentially eliminated. This method had not evolved in time to be used for the PABST program, but is being seriously considered for future use.

3.8 BONDING OPERATION

3.8.1 Adhesive Application

Adhesive films are very sensitive to moisture absorption and appropriate precautions are necessary to reduce moisture in the layup room. The area where adhesive layup is performed should be an environmentally controlled area. Adhesive layup is not difficult, but there are a couple of problems on the PABST program that merit consideration for production.

One of these is that improvements should be sought which do not trap as much air in the wide area doublers, so that voids can be reduced to ease the burden on inspection. No such trapped bubble encountered on PABST was structurally significant, but the occurrences were sufficiently frequent to be disconcerting to those not acquainted with the stressing of adhesive bonds. Perforating the doublers prior to anodizing would appear to be a promising technique to pursue or reformulate the adhesive film to one-side-tacky (OST).

A second problem involved the need for multiple thicknesses of adhesive film in local areas. Verifilm was used on the bonded assemblies to

identify those areas needing multiple layers of adhesive. The fit of details with the male tool was sufficiently good that less expensive visual fit checks appeared sufficient for production when used in conjunction with good detail inspections. Most of the adhesives used today are supported adhesive films which have an impregnated carrier fabric. These films can be ordered precut to the needed width dimensions from the manufacturer; otherwise this would be a time consuming cutting process for production.

CAUTION

Because the adhesive film is very hygroscopic, it must be properly stored and handled with care. If the adhesive is cured with an excessive moisture content, there is a considerable loss in durability of the joint. This is not apparent from the standard lap shear tests.

3.8.2 Preparation For Cure

Preparation for cure includes the critical bagging process. Bagging is critical because if a bag fails during cure, all the time spent fabricating details, in prefit and processing can be lost.

The selection of bleeder fabric, vacuum bag film, and sealing compound is very important. Some of the new types of bleeder fabric are very hygroscopic. Any moisture allowed to come in contact with the bleeder will be absorbed, whether in storage or in the production area and contaminates the adhesive.

The bleeder fabric selection should be based on the amount of elongation required to stretch over shear tees, longerons, and intercostals without bridging across corners or in pockets and also have good wickability where it doesn't seal-off under pressure so that it is able to absorb the adhesive resin bleed out.

By and large, the PABST experience with regard to the use of bleeder material was that the best panels used the least material, even though it meant more care in applying the vacuum bag. The generous use of bleeder

material to avoid bag puncturing and bridging led to visible mark-off on the skin at some of the stiffener locations. Subsequent work indicates that complete omission of the bleeder material may be both more economical and conducive to higher quality parts.

The vacuum bagging film must be able to withstand substantial pressure as well as heat and long duration cures. It must also provide enough elongation to be drawn down into deep pockets without the vacuum bag rupturing. Proper bagging is best accomplished by allowing generous overlaps in the bag during application. Otherwise a bridged condition can exist and cause severe cans in the skin using the male bond tool, and/or cause voids in the faying surfaces using the female bond tool. Wrinkles in the bag can be worked out under partial vacuum.

The vacuum sealing compound should be able to withstand the cure temperature and pressure without becoming soft and pulling away from the bond tool and vacuum bag during the cure cycle. It should also be able to be easily removed from the bond tool after cure.

Another consideration for production is to design the bonded assembly around a multi-stage bond in which the bond tool and bonded assembly would not have to be vacuum bagged and autoclave cured. Ideally, the multiple stage bond tools would apply mechanical pressure to the faying surfaces and incorporate integrated heaters. That would eliminate the autoclave requirement completely and only those bond details needed for each stage would have to be present for assembly. The FSDC was designed before consideration of the potential advantages of multiple stage bonding was possible and against a background of industry problems with multi-stage bonding, particularly over the adhesive flash. Therefore all the FSDC panels were a single stage bond. The two key distinctions between single and multi-stage bonds are the complexity of the holding fixtures required to locate all of the parts and the necessary bagging to apply uniform pressure for a single stage bond. These single stage operations can be sufficiently more difficult than those needed to bond only part of the assembly at a time to warrant further development of bonding techniques based on multiple bond cycles, with each stage being simple and reliable. Another potential advantage of multi-stage

bonding is the apparent feasibility of implementing a simple system for the automated inspection of bond quality.

During the PABST program an extensive number of hours were expended in the developmental application of bleeder fabric; flash breaker tape, Figure 45; and vacuum bagging for the autoclave cure cycle (40 psi @ 250^{O}F for 90 minutes). Once the cure was completed, additional hours were required to remove the vacuum bag, the bleeder fabric, the flash breaker tape, and to grind off the excess adhesive flash, Figure 46, to facilitate inspection of the bonds. This laborious R&D process was obviously not economical for production. Subsequent to the building of the FSDC panels, it has been shown that superior results can be obtained by omitting the bleeder fabric and flash breaker tape and just bagging directly onto the part. This is accomplished by working any trapped air bubbles out by hand after a partial vacuum has been drawn on the bag. This is not practical for the PABST-type single-stage bonding of intersecting stiffener panels which have pockets in the vacuum bag, but is quite feasible for bags which can be folded to a single-curvature configuration.

Further development work is being conducted on bonded assemblies where the autoclave is not used, to determine the amount of pressure required and develop tooling concepts as necessary to achieve quality bonded results.

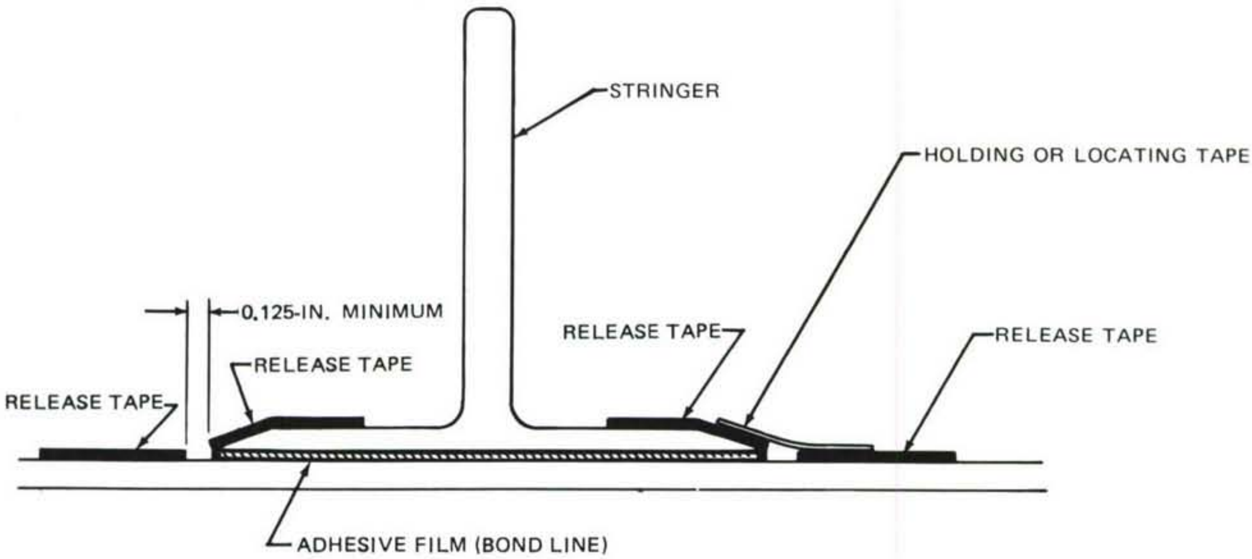


FIGURE 45. TYPICAL FLASH-BREAKER TAPE APPLICATION

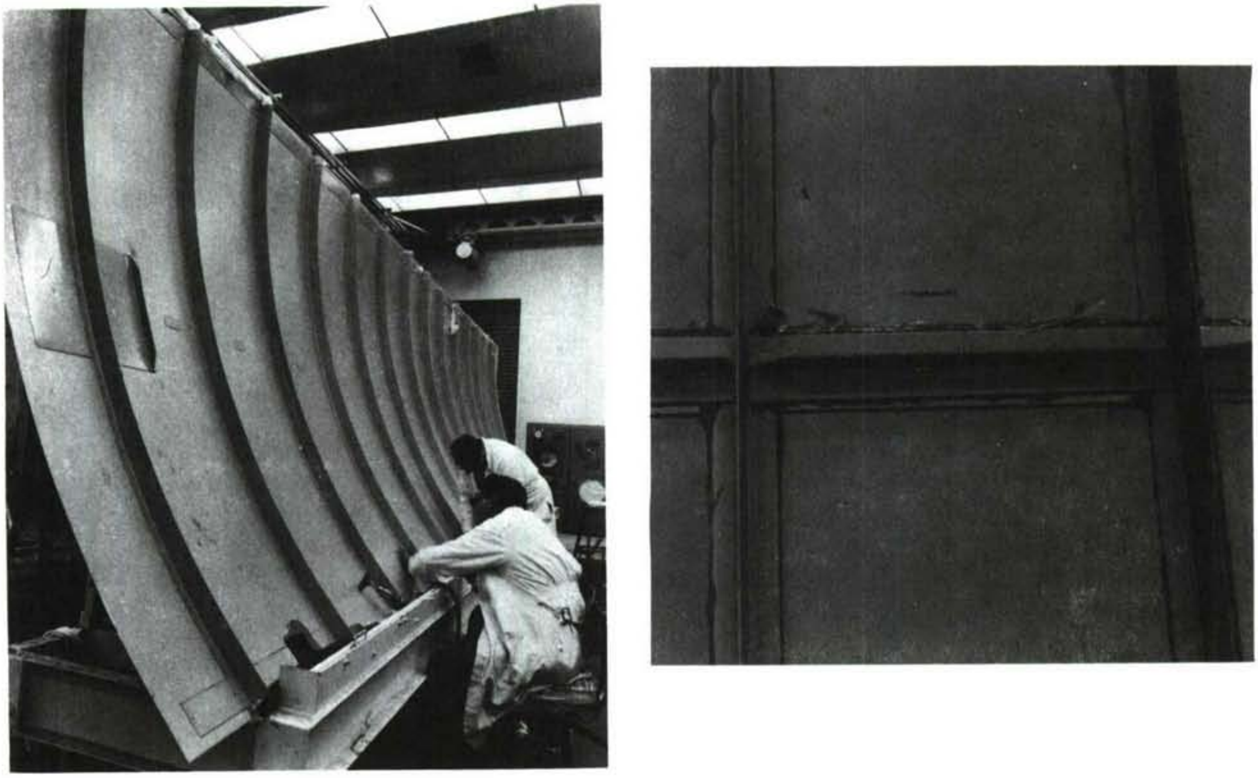


FIGURE 46. GRINDING ADHESIVE FLASH FROM PANELS

SECTION IV
QUALITY ASSURANCE

4.1 BACKGROUND

This section delineates the manner in which Quality Assurance (QA) was integrated into the Design & Fabrication of the Full Scale Demonstration Component (FSDC). The QA goal during Phase III was to assure the integrity and durability of the adhesively bonded primary structure. Figure 47 summarizes the QA involvement in the PABST program. The efforts illustrated here represent a minimum QA program model which can serve as a guide for any organization fabricating adhesively bonded assemblies.

State-of-the-art QA procedures were utilized during the PABST program; however, it is apparent that to be cost-effective a new generation of Quality Control (QC) equipment, methods, and procedures should be investigated and developed. The primary areas presently being investigated are discussed in paragraph 4.24 of this report.

4.2 RECEIVING INSPECTION - RAW MATERIAL TESTING

The standard aluminum materials were chemically, dimensionally, and physically tested to the applicable QQ-A-250 specifications.

Aluminum alloys 7049 and 7475 were additionally traceable by supplier lot number to its end use on the assembly. The traceable identifier was also recorded on the Fabrication Outline (FO).

4.2.1 Receiving Inspection - Adhesive Primer & Adhesive Film

The adhesive primer and adhesive film were tested to the requirements shown in Figure 48. Both adhesive materials were received with supplier's certified test reports and were traceable by lot number to their end use on the assembly. The traceable identifier was also recorded on the FO. These materials were tested, accepted, and Perishable Item Labels were attached to each roll of film and container of primer noting the shelf life and storage

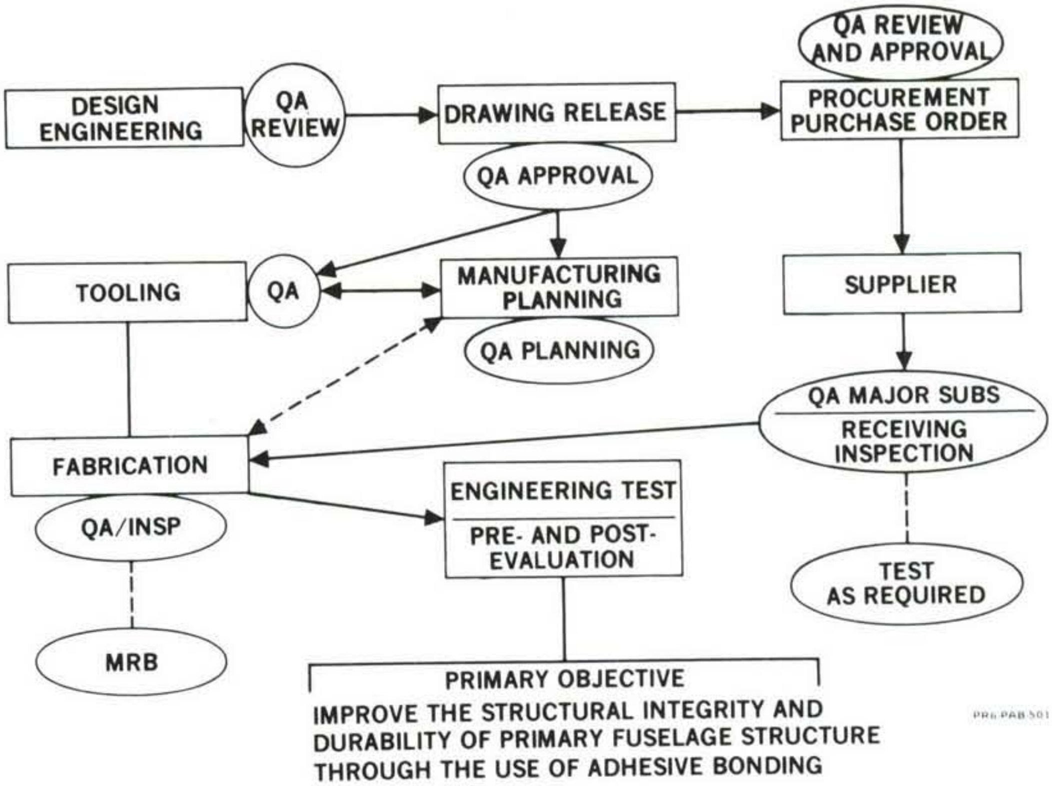


FIGURE 47. QUALITY ASSURANCE PLAN

INCOMING RECEIVING TESTS

ADHESIVE PRIMER

- RT LAP SHEAR — 5000 PSI (MIN)
- RT "T" PEEL — 15 LB/IN. (MIN)
- RT CLIMBING DRUM — 18 IN.-LB/IN./3-IN. WIDTH (MIN)
- PERCENT SOLIDS — 10 ± 1 PERCENT

ADHESIVE FILM

- RT LAP SHEAR — 5000 PSI (MIN)
- RT "T" PEEL — 15 LB/IN. (MIN)
- RT CLIMBING DRUM — 18 IN.-LB/IN./3 IN.-WIDTH (MIN)

SHELF-LIFE: 90 DAYS AT 0°F

PR6-PAB-584B

FIGURE 48. ADHESIVE FILM AND PRIMER

requirements. Chemical characterization is being accomplished by MCAIR as part of a satellite program. Paragraphs 4.23.4 and 4.23.5 of this section address the importance of chemical control.

4.2.2 Working Life of Primer and Adhesive

The adhesive primer was removed from $0^{o}F$ storage and allowed to warm to room temperature in it's sealed container. The adhesive primer was applied to the phosphoric acid anodized surface to a dry film thickness of 0.0001-0.0003 inch. The primer was force cured after a 30 minute room temperature (RT) air dry, at 235-265^{o}F for 50 to 70 minutes. The maximum elapsed time, from application of adhesive primer to final curing of the assembly, was 96 hours. The maximum permissible out-time for bulk primer at 70-90^{o}F is five days.

The adhesive film was removed from $0^{o}F$ storage and allowed to warm to room temperature in its sealed container. Once the original seal is broken, care must be taken to prevent the adhesive film from absorbing moisture. Thus, the adhesive film is applied to the faying surface of the assembly in a controlled environment and then the assembly is vacuum bagged and cured at 235-265^{o}F for 90 to 100 minutes at 40 ± 5 psi. The maximum permissible accumulated out-time for adhesive film at 70-90^{o}F is five days.

4.3 CHEMICAL ANALYSIS - FABRICATION

The process tanks were chemically analyzed on a predetermined frequency based on past analysis of the solutions.

For example: Engineering specifies the alkaline cleaner concentration tolerance as 6 to 8 ounces per gallon. The Quality Engineering-Process Control Warning Limit Range for the alkaline cleaner is 6.2 to 7.8 ounces per gallon. The frequency of analysis of the alkaline cleaner, Amchem 6-16, and deionized water varied throughout the program as these tanks and solutions were also being used for production details. The alkaline cleaner tank was analyzed weekly, but if two successive weekly analyses showed the solution to be outside the warning limit range, the frequency of

analysis was to be increased. And conversely, if five successive weekly analyses showed the solution to be within the warning limit range, the frequency of analysis was to be reduced to once every two weeks. The purpose in using "warning limit ranges" is to prevent solution concentration from exceeding the engineering requirements and eliminate the need to reprocess production parts.

4.4 POLARIZING LENS INSPECTION - PHOSPHORIC ACID ANODIZED SURFACE

A photographic polarizing lens was used by the QA inspector to view the reflected image of the anodized details as shown in Figure 50. While viewing the detail surface, the polarizing lens was rotated 90°. An acceptable anodic coating was verified by an observed change in interference colors. The most frequent colors are purple, yellow, blue and green hues. Alternate inspection methods for verifying proper phosphoric acid anodize of details are discussed in paragraph 4.24.1 on page 93.

4.5 WEDGE CRACK SPECIMEN TESTING FOR SURFACE TREATMENT VERIFICATION

Wedge crack plates were processed concurrently with the PABST bond details. These 6 by 6 by 1/8 inch thick plates were fabricated from 7075T6 non-clad aluminum. One plate was placed in each electrical string of parts on a large rack during the cleaning and anodizing process. Each plate was identified to the rack of details being anodized. After anodize the plates were primed with BR127, bonded with FM73, and cut into five one-inch-wide specimens.

CAUTION

> Extreme care must be exercised when cutting the five wedge crack specimens from each bonded plate since the bondline can be easily overheated when a dull saw or an excessive cutting speed is used. An overheated bondline will cause a local disbond with a resultant increase in crack growth.

A one-inch-wide by 1/8 inch thick 7075T6 bare aluminum alloy wedge was driven into one end of the 1 by 6 inch specimen to a depth of approximately

one inch; thereby fracturing the bondline. This initial crack length was measured and recorded prior to subjecting the specimens to the designated environmental exposure; namely, 140°F and 95-100 percent relative humidity for one hour.

After exposure, crack growth was again measured and documented and then the wedge was driven further into the bondline until the bonded specimen separated. The specimens were examined, and to be acceptable, the failure mode must be 100 percent cohesive. If any specimens failed adhesively, all the details in that particular string were reprocessed.

4.6 ROOM TEMPERATURE LAP SHEAR TESTING

Lap shear coupons were processed (anodized) concurrently with the PABST bond details. These 4 by 6 by 0.063 inch thick specimens were fabricated from 7075T6 non-clad aluminum, primed with BR127, bonded with FM73, and cut into four one-inch-wide coupons. Specimens were then tested at room temperature for lap shear strength where the minimum acceptable value is 4000 psi for this in-process control specimen.

NOTE

> The required production values are 1000 psi lower than the incoming test requirements. The reason for this difference is that the coupons were prepared and bonded in a production mode as compared to the laboratory prepared coupons for receiving inspection. Incoming tests were performed under exact lab conditions and controls which cannot be duplicated in production areas. The ultimate shear properties were thus obtained. Production values were established after evaluation of production curing methods and shear value scatter.

4.7 QUALITY ASSURANCE APPROVAL - DETAIL DESIGN

The Engineering Design drawings (EDs) were reviewed prior to release by cognizant QA and Materials and Process Engineering (M&PE) NDT personnel. These personnel reviewed the drawings to verify that quality requirements were properly specified and NDT methods could be efficiently applied.

Signature acceptance on the vellum prior to release of the drawing was required.

4.8 MATERIAL REVIEW BOARD (MRB)

All discrepancies were submitted via the Failure Rejection Report to the Material Review Board for disposition. The MRB was composed of designated Design Engineers, Stress Engineers, Material Process Engineers, and Quality Engineers.

Discrepancies were dispositioned as follows: 1) Rework, 2)Acceptable "As Is", or 3) Scrap. The engineer dispositioning the discrepancy was required to state rationale for accepting a condition. The FRR was cleared by Quality Assurance.

4.9 DETAIL TOOLING INSPECTION

Tools used on the PABST Program were dimensionally inspected to the Tool drawing (TD) requirements. Typically, the tools were fabricated to one half of the ED tolerance requirements. For example, where the ED requires a ± 0.015 inch dimension for the detail; the TD would specify a tolerance of $\pm$ .0075 inch.

4.9.1 Bond Tool Inspection

The bond tools were dimensionally inspected to the TD's. Using dummy details, Quality Assurance Tooling thermocoupled the entire tool and ran it through the bond cure cycle. The rate of temperature rise and hot and cold spots were identified. The coldest and hottest thermocouple locations were used as monitoring locations for all subsequent cure cycles. This information was added to the Fabrication Outline Special Page (FOSP). A minimum of two thermocouples was mandatory; typically however, ten to twenty thermocouples were inserted for the actual cure cycle of the PABST assembly. The number of thermocouples is generally dictated by the size and configuration of the panel.

4.10 DETAIL INSPECTION - FABRICATION

The details used during the fabrication of the FSDC were inspected to the ED requirements. Additionally, extrusions were inspected in the area of the flange after forming for a maximum concave deformation of 0.015 inch and a maximum convex deformation of 0.010 inch. These tolerances were required to prevent excessive rework of the formed extrusion bond details and were approved by Stress Engineering. The problems encountered were attributed to inadequate forming tools and the initial design of the extrusion. The aforementioned problem was solved by adding a note for QA inspection verification to the FO of a FOSP.

4.11 PREFIT INSPECTION - FABRICATION

"Prefit" is a term used to describe the "dry-run" manufacturing operation where the bond details are first assembled without adhesive film. The details are assembled in/on the tool and then techniques are developed for supporting the details during the bond cycle.

During the PABST program this support was achieved using tack rivets, undersized bolts, nuts, etc. Small holes were added in detail parts for attaching clips and springs to support the details on the racks during the anodic process. The locations for these holes were either as specified by Stress Engineering and were re-sized on assembly for installation of standard fasteners; or else they were added outside of the critical bond area to accommodate Manufacturing requirements. The details were identified by vibratory pencil to maintain traceability to a specific assembly and FO.

Stress Engineering also specified the area where the details were to be identified. The bond details were previously inspected by QA and the prefit inspection was accomplished by visual examination. The QA inspector was allowed to apply a maximum of five pounds pressure to force parts into their proper relative positions. The maximum allowable mismatch at the faying surface is 0.007 inches. Mismatches in excess of 0.007 inches required a Failure Rejection Report (FRR) and rework of the discrepant detail by Manufacturing.

The large size and nature of the pre-bond assembly made prefit inspection very difficult. The female tool caused a major problem for QA because it was impossible to verify prefit tolerances on the external doublers since they are sandwiched between the bond tool and the fuselage skin. Verifilm inspection was the only method used for this determination.

4.12 VERIFILM INSPECTION - FABRICATION

"Verifilm" is the process whereby the prefit details are assembled using a verifilm material enveloped between two pieces of mylar in each joint where the adhesive would normally be placed for bonding. The verifilmed assembly is then cured in the autoclave at 225-245^{o}F and 40$\pm$5 psi for 15 minutes, minimum. The temperature, pressure, and time charts are analyzed by QA to assure the three parameters meet Engineering requirements. In-process inspection personnel monitored the production personnel during this phase. After the verifilm cure cycle was complete, the pre-bond assembly was disassembled and the verifilm physically marked with the actual measured thickness. The verifilm is visually inspected to detect slippage or mislocation of details, and indicate wherever locating pins do not allow the details to seat properly. Improperly fitting details were reworked and where necessary, additional verifilm inspections were performed. All areas on the verifilm 0.010-0.020 inch thick were identified on a controlling ED.

All areas exceeding of 0.020 inch thick were rejected on FRRs for Engineering disposition. M&PE and QA personnel reviewed all verifilms and added notes to the FOSP where additional layers of adhesive needed to be added during the bond cycle. Signature "buy-off" on the FO by QA and M&PE was verified by QA Inspection prior to release of the bond details for the anodize process.

4.13 PHOSPHORIC ACID ANODIZE

The details were wiped clean with a solvent, MEK (Methyl Ethyl Ketone), prior to racking. After the details were racked, reference Figure 43, they were inspected by QA to assure the following: that the details were free from physical damage, marks, and verifilm residue; that electrical contact

was evident; that wedge crack specimens were present in each electrical chain of parts, and that the lap shear coupons were included on the rack. The details were anodized as delineated in Figure 49. The anodized details were immersed in room temperature tap water within 2 minutes (maximum) after completion of anodize. A visual inspection was made for a water-break-free surface on the anodized details after immersion in tap water rinse for 10-15 minutes and prior to the deionized water spray rinse.

WARNING

> This maximum 2 minute delay is critical as the phosphoric acid anodize solution will start to remove the oxide coating as soon as anodic current is "turned off".

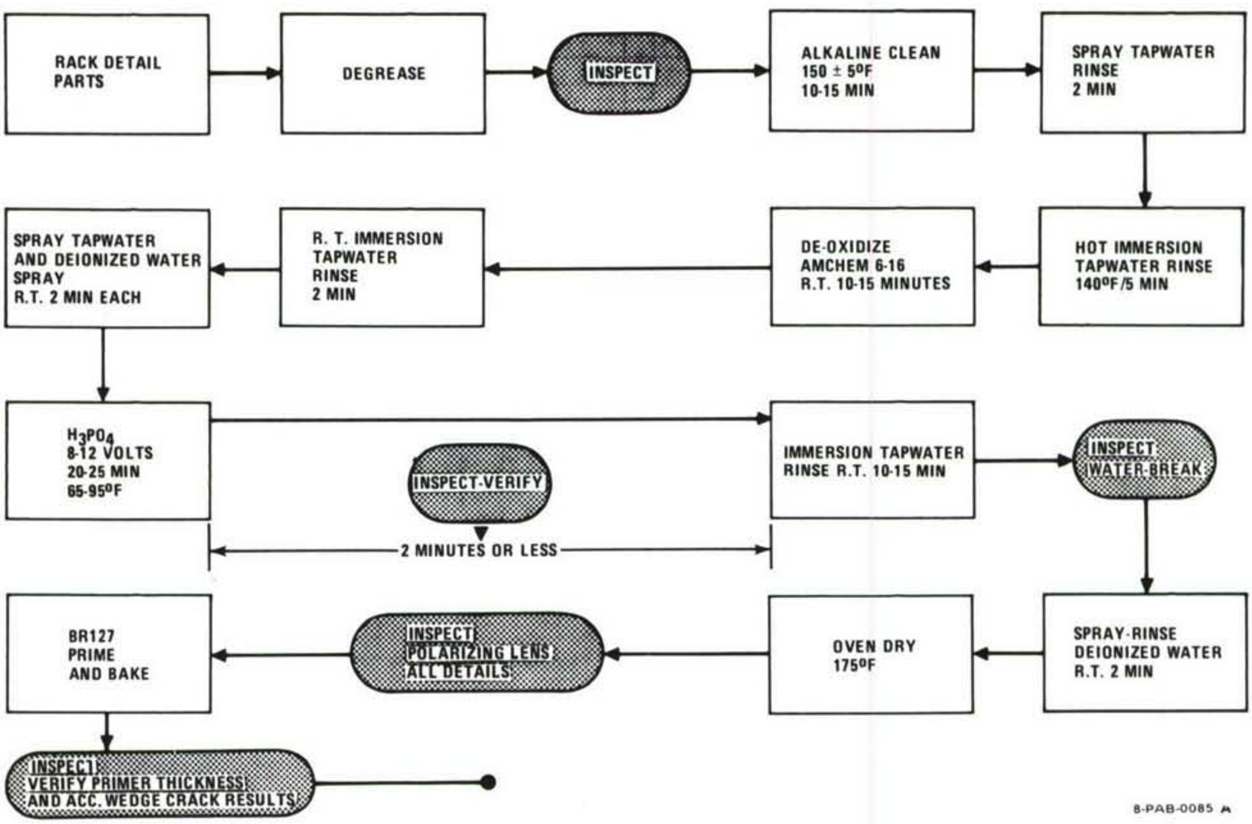


FIGURE 49. SURFACE TREATMENT

4.14 INSPECTION OF THE ANODIZED DETAILS

QA Inspection examined all details for uniform color changes with a polarizing lens as shown in Figure 50. Non-uniformity in appearance of the details indicates inadvertent contamination and fracturing of the aluminum oxide film. If this condition is observed, the details are rejected on an FRR and reprocessed. Contamination prevention is important.

4.15 ADHESIVE PRIMER APPLICATION INSPECTION

While the parts were still on the anodic racks, the BR127 primer was applied using a recirculating spray system. This was required due to the high settling characteristics of the BR127 primer non-volatiles. The primed details were air dried for a minimum of 30 minutes at RT and force cured for 50 to 70 minutes at 235-265^{0}F.

Quality Assurance Inspection verified that: 1) the batch number of the adhesive primer used was added to the FO; 2) the details were primed following anodize within 2 hours after completion of oven dry at 175^{0}F; 3) the applied BR127 was oven cured for the prescribed time as evidenced by oven cure charts; 4) the primed details have adequate primer application; 5) the wedge crack specimens are moved to the laboratory for test; and 6) that the primed details are removed from racks and wrapped with neutral kraft paper and moved to the bonding production area.

NOTE

> The details were anodized and primed on the same production rack to prevent handling and subsequent damage and contamination of the anodic surface prior to adhesive priming.

4.16 QUALITY ASSURANCE WEDGE CRACK SPECIMEN VERIFICATION

The wedge crack specimens were inspected with a Permascope to determine that the required dry film thickness of 0.0001 - 0.0003 inches was applied. The specimens were then bonded and tested. QA verification that

- THE ANODIZED SURFACE IS ILLUMINATED USING A MERCURY VAPOR OR FLUORESCENT LAMP.
- A PHOTOGRAPHIC POLARIZING FILTER IS PLACED BETWEEN THE OBSERVER AND THE REFLECTED IMAGE OF THE PARTS. (SEE ILLUSTRATION FOR EXAMPLE.)

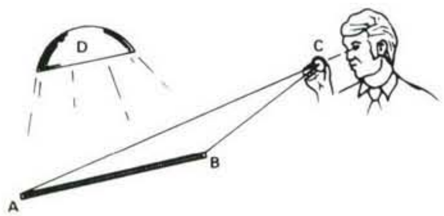


FIGURE 50. ANODIC COATINGS ACCEPTANCE TEST

wedge crack tests were acceptable prior to laying up of the bond details was accomplished.

These specimens were used to verify that the anodic surface was properly prepared and that the adhesive primer thickness was within specification tolerances. Since they were batch processed with the production details, these specimens experienced actual process conditions.

During phases IB and II, a total of 1123 specimens were tested, of which 31 were rejections. These rejections all occurred in September 1975. Subsequently, QA shut down the production anodizing tank system until the problem was resolved. The problem was determined to be due to contamination caused by handling of the details prior to primer application. At that time, a caution note was added to the Engineering requirements to prohibit the handling of the bonding surface of the details from the time of anodize through application of the adhesive primer.

During phase III, all 1120 specimens tested exhibited an acceptable cohesive failure mode.

NOTE

> Tests at Douglas Aircraft have demonstrated that handling of chromic acid anodized and FPL-etched details prior to application of the adhesive primer causes contamination similar to that experienced with PABST phosphoric acid anodized test panels.

4.17 LAYUP INSPECTION

"Layup" describes the procedure for adding the adhesive film to the anodized and primed faying surface of the details to be bonded. This requires the use of clean white cotton gloves and a controlled environmental area under QA surveillance. QA's responsibility is to verify that the batch number of the adhesive film is added to the FO; that the details are layed-up to the requirements of the ED, and in the same manner as used during the prefit process; that the extra layers of the FM 73 adhesive film is applied when specified in the FOSP; and that lap shear coupons are placed on the assembly. QA also verified that the pressure plate, thermocouples, etc., were installed, the assembly was bagged, and the leak rate on the vacuum bag was less than 0.5 inch of Hg vacuum/minute.

4.18 FINAL PRE-CURE INSPECTION

Once the vacuum bagged assembly was moved into the autoclave, QA inspection verified that the leak rate of the assembly was within the allowable range per specification prior to application of temperature and pressure. The bag is vented to atmosphere when the autoclave pressure is 10 psi. QA Inspection also verified that the assembly was cured for 90 to 100 minutes at 235-265^{o}F and 40$\pm$5 psi; and at a heat-up rate of 1-7^{o}F/min. Prior to autoclave venting, the bonded assemblies were cooled to a maximum of 150^{o}F.

4.19 BONDED ASSEMBLY INSPECTION

QA inspectors checked each assembly dimensionally for shifting of details, and visually for removal of adhesive flash to allow adequate NDT and physical damage inspection. Additionally, bonded panels were visually inspected for frothy and/or cracked gluelines and for lack of fillets in the glueline. Discrepancies found were documented on FRRs.

Lack of filleting was observed on several panels. These areas were submitted to Engineering on an FRR and were subsequently either filled with a cold set-adhesive (EA9309, EA9312) or dispositioned "acceptable as is".

4.20 ROOM TEMPERATURE LAP SHEAR PROCESS CONTROL TESTING

The lap shear coupons were cut into four one-inch-wide strips and tested. Because they were cured simultaneously with the bagged assembly, these specimens were used to check the adhesive strength after the specified time exposure to temperature and pressure during the autoclave cure cycle. The specimens were therefore representative of the assembly with which they were cured.

During phases IB and II however, 742 specimens were tested and there were 67 rejections. Examinations of these rejected specimens revealed two causes for failure: 1) tapered gluelines, the result of improper shimming; and 2) "burned edges" of the glueline, the result of a dull cutter or an excessive cutting feed rate. Both causes were eliminated by revised instructions to appropriate personnel emphasizing proper coupon preparation procedures.

All 175 specimens tested during phase III exceeded the acceptable shear stress minimum of 4000 psi.

4.21 NONDESTRUCTIVE TEST INSPECTION

The primary NDT inspection instruments used during the PABST Program were the Fokker Model 70 and the NDT Instrument Incorporated Model 210 Bondtester. The Fokker Bondtester was used on the majority of bonded panels because strength cohesive correlation curves were developed using this bond tester. The 210 Bondtester was used primarily for areas of the bonded panels where the Fokker probe, because of its configuration and size, could not be accommodated. The QA personnel who performed the NDT inspections of the FSDC were level II Ultransonic Inspectors qualified to MIL-STD-410D and Douglas Aircraft Company (DAC) NDT inspection sections of the training manuals.

To be NDT qualified, DAC requires a minimum of 76 hours classroom training and 2 years on-the-job-training. MIL-STD-410D requires a minimum of 36 hours classroom training and 1 year on-the-job-training.

The "design allowables" were established by DAC Stress Engineering and the requirements were incorporated into the applicable Engineering requirements. Prior to NDT of each bonded panel, a written procedure and inspection technique was established by Quality Engineering NDT personnel and were approved by M&PE.

These procedures are specific for each assembly and are contained in the QA NDT document identified as Quality Assurance Ultrasonic Technique - PABST, Part Numbers/Bonded Assembly. These procedures contain as a minimum: 1) Part or configuration to be tested, detail part thickness, alloy and temper, and adhesive system used; 2) Manufacturer and model number of instrumentation to be used for the bondline test; 3) Model or designating number of the probe/adapter to be used for the test; 4) Reference standards serial number and design description; 5) Couplant; 6) Method and frequency of instrument calibration; 7) Testing plan; and 8) Acceptance limits for each joint as required by the Engineering specification.

QA Ultrasonic Inspection personnel inspected the panels as required by the Approved Quality Assurance Technique. Figure 51 delineates the class of joint inspected and defines in the notes where these classes were applicable. Figure 52 shows the Fokker cohesive bond strength acceptance limits for a single bondline. The reference to additional layers of adhesive film being used in a joint was compensated for by the permanent marking on the panel verified by QA Inspection for adjustment by the ultrasonic inspector of these readings, reference note (1) in Figure 52. Figure 53 illustrates the acceptance grades for voids or unbonds. Figure 54 shows a typical quality zoning of PABST bonded joints. Grade 1, reference Figure 53, was the first 1/2 inch from the edge of the member (longeron or longitudinal skin splice). Figure 55 illustrates Typical Lap Shear Strength vs. Fokker Bondtester Quality Units. A strength curve, as shown, was developed for each combination of facing sheet alloy and material thickness.

All of the PABST bondlines were ultrasonically inspected and the following information was permanently marked on the panels: The perimeter of disbonded or lack-of-bond areas were outlined on the panels and

(K)	APPLICABLE FOR SINGLE BOND LINES AND DOUBLE BOND LINE SPLICE JOINTS.	
FOKKER	CLASS A GREATER THAN 80%	(SEE NOTES) (1) (2) (3)
COHESIVE	CLASS A/B GREATER THAN 65%	
BOND STRENGTH	CLASS B GREATER THAN 50%	
QUALITY	CLASS C GREATER THAN 25%	
CLASSES		

NOTES: (1) SKIN/STRINGER AND SKIN/FRAME BONDS SHALL BE CLASS A MIN.

(2) DOUBLER/SKIN BONDS SHALL BE CA CLASS A/B MIN.

(3) SKIN SPLICES JOINTS (DOUBLE BOND LINES)SHALL BE CLASS A MIN.

FIGURE 51.

LOWER SHEET THICKNESS (INCHES)	MODEL 70 PROBE	UPPER LIMIT	LOWER LIMITS(1)			
			CLASS A 80%	CLASS A/B 65%	CLASS B 50%	CLASS C 25%
0.040	3814	>R8	>L54	>L40	>L25	>L10
0.050	3814	>R10	>L48	>L36	>L20	>L9
0.063	3814	>R12	>L42	>L30	>L18	>L8
0.071	3814	>R16	>L40	>L28	>L17	>L7
0.081	3814	>R18	>L38	>L25	>L15	>L6

(1) ADDITIONAL ADHESIVE LAYERS SHALL NOT YIELD READINGS LESS THAN THE LOWER LIMITS BY THE FOLLOWING FACTORS: 2 LAYERS (-15); 3 LAYERS (-25); 4 LAYERS (-30)

FIGURE 52. FOKKER COHESIVE BOND STRENGTH ACCEPTANCE LIMITS

PR7-PAB-0104 A

cross-hatched. Low bond strength areas were outlined and Bondtester shift noted on the panels. On the FSDC skins, permanent lines outlined the locations of the internal shear tees and the internal longerons. This facilitated the inspection of the bondlines before and during the testing of the panels. These areas of disbond and lack-of-bond, were permanently identified during Phase III of the PABST program in order to simplify reinspection during testing in Phase IV. A major purpose of full scale testing was to ascertain if these disbonds or areas of weakness would grow, and to provide data for further evaluation at the end of Phase IV - Tear Down Inspection.

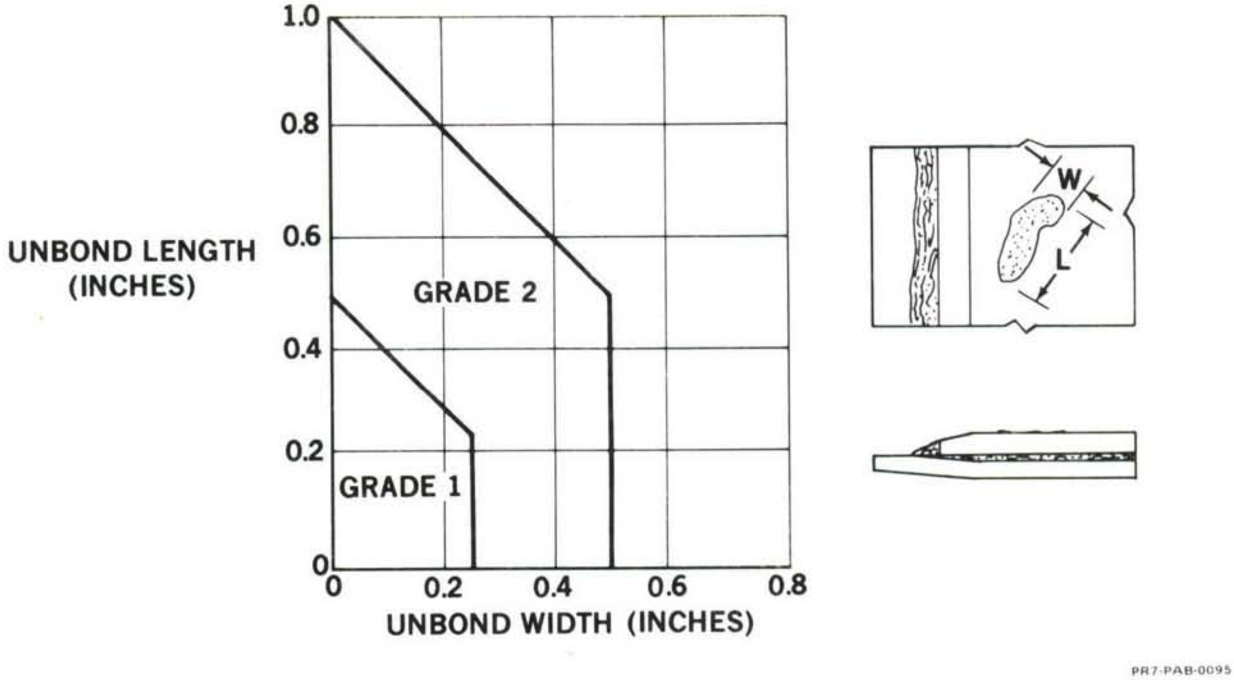


FIGURE 53. DEFINITION OF ACCEPTANCE GRADES FOR VOIDS OR UNBONDS

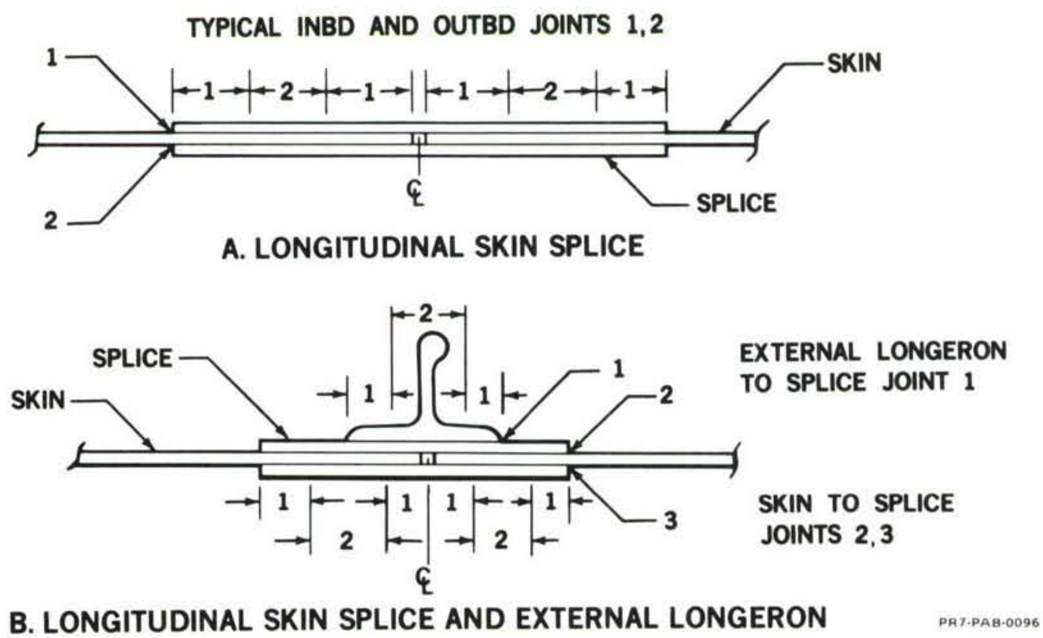


FIGURE 54. TYPICAL QUALITY ZONING PABST BONDED JOINTS

(FACING SHEETS ARE 7075-T6 Al/2024-T3 Al OF THICKNESS 0.050 IN./0.050 IN.)

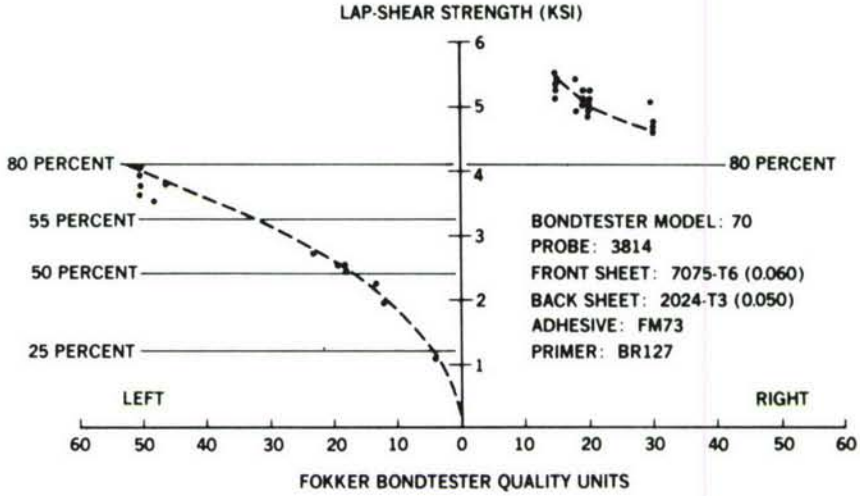


FIGURE 55. LAP-SHEAR STRENGTH VERSUS FOKKER BONDTESTER QUALITY UNITS

Figures 56 through 65 show the permanent markings resulting from ultrasonic inspection of the PABST bonded panels. The following panels demonstrate a cross section of typical problem areas:

1) Panel UJ197703 - Figures 56 and 57; unbonds developed during bonding of this nonconstant section panel which has a heavy external doubler around the door (not cut out in this photo);

2) Panel J197709 - Figures 58 and 59; unbonds and low bond strength associated with the large doubler areas in this panel. The large doubler was assembled to the aft pressure cylinder of the test fixture;

3) Panel UJ197715 - Figures 60 and 61; same problems as in 2 above for the large doubler areas installed under the wing box;

4) Panel UJ197714 - Figures 62 and 63; also same as in item 2 above for the large doubler assembled into the aft pressure cylinder of the test fixture; and

5) Panel UJ197712-401 - Figures 64 and 65; shows complete unbond of a shear tee due to mylar left on adhesive when layed up. Engineering disposition required rivets to be added as per completed FRR.

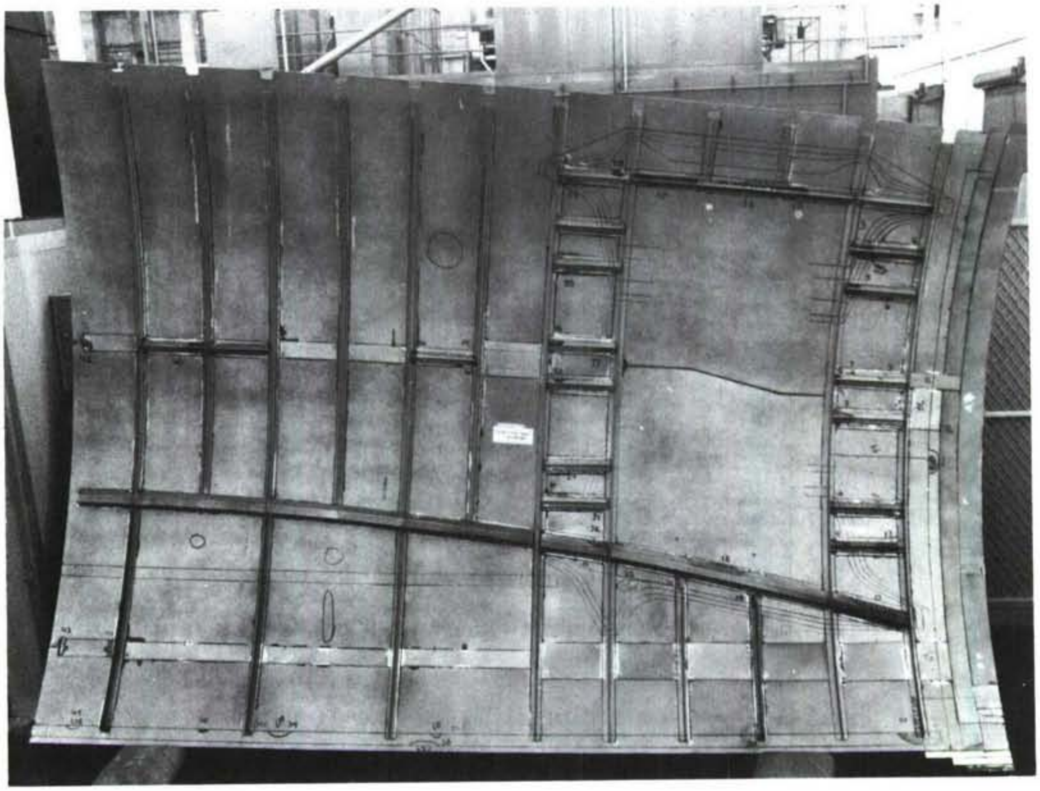


FIGURE 56.

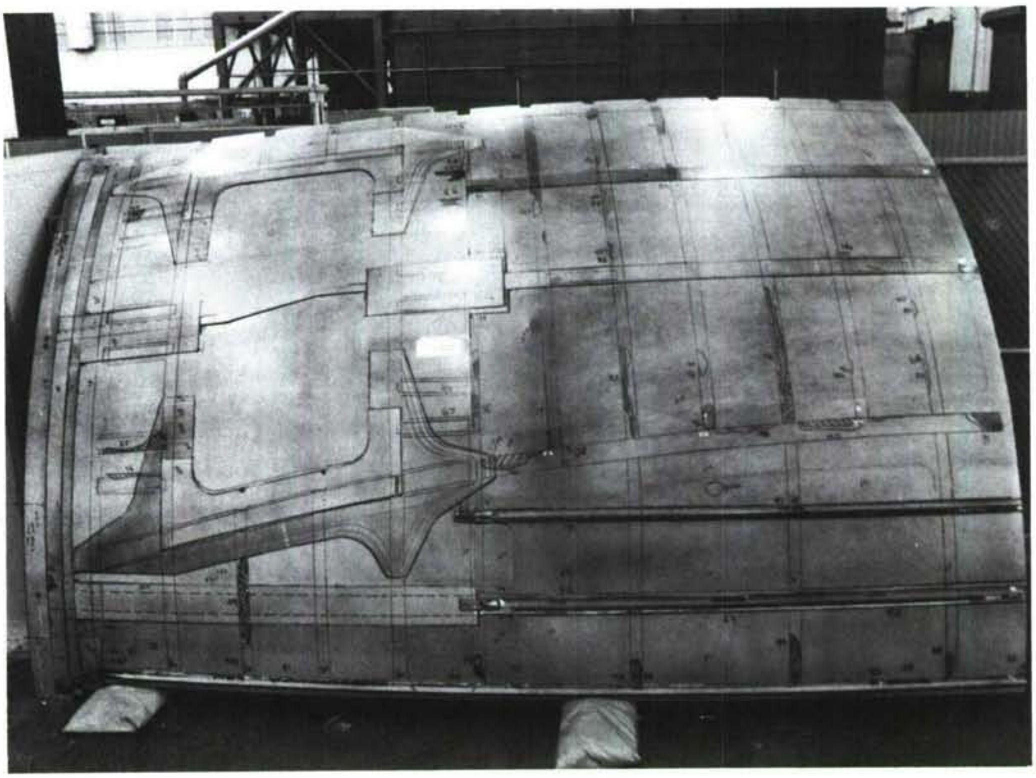


FIGURE 57.

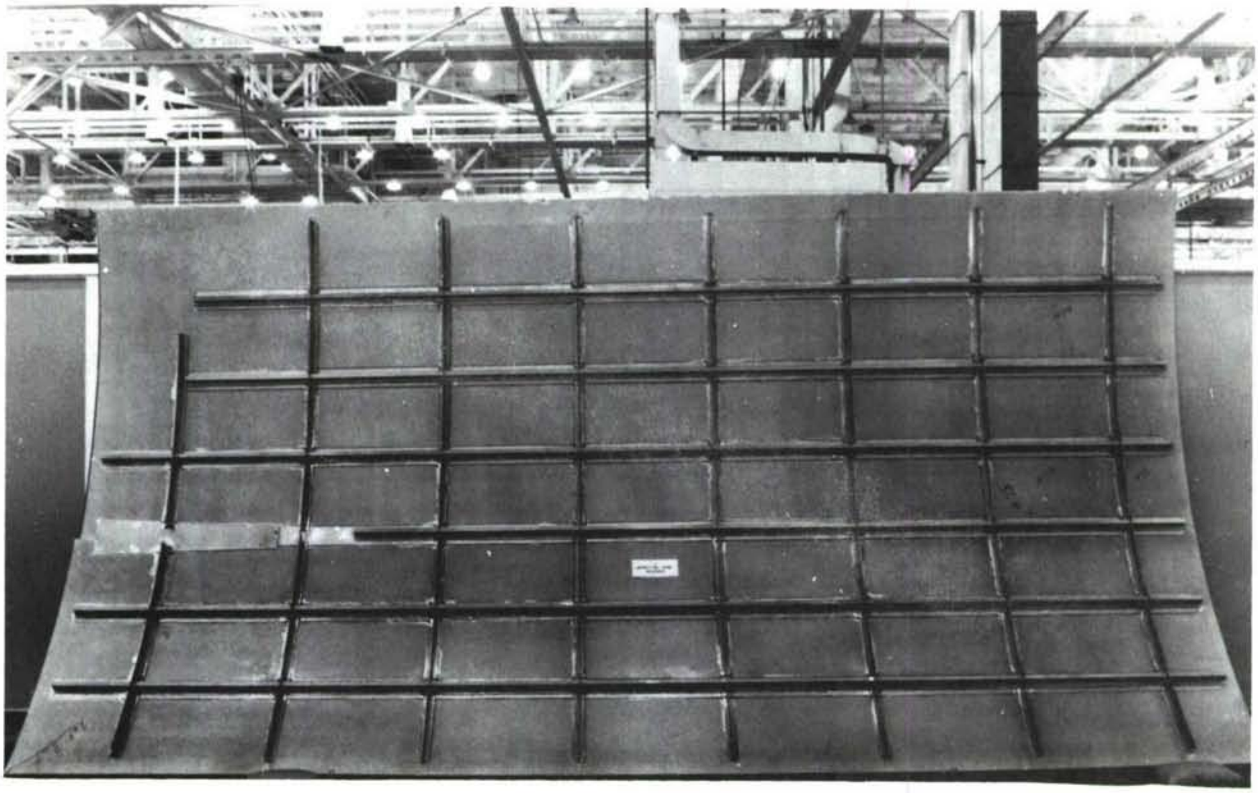


FIGURE 58.

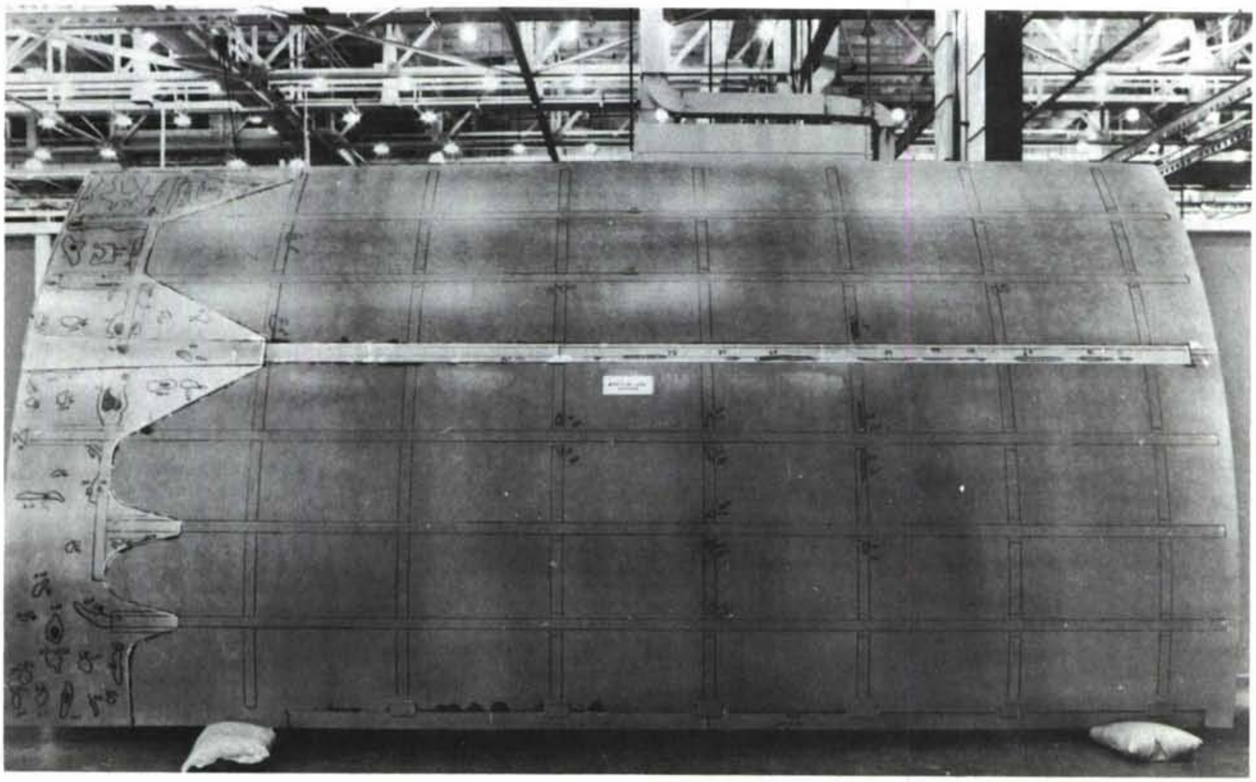


FIGURE 59.

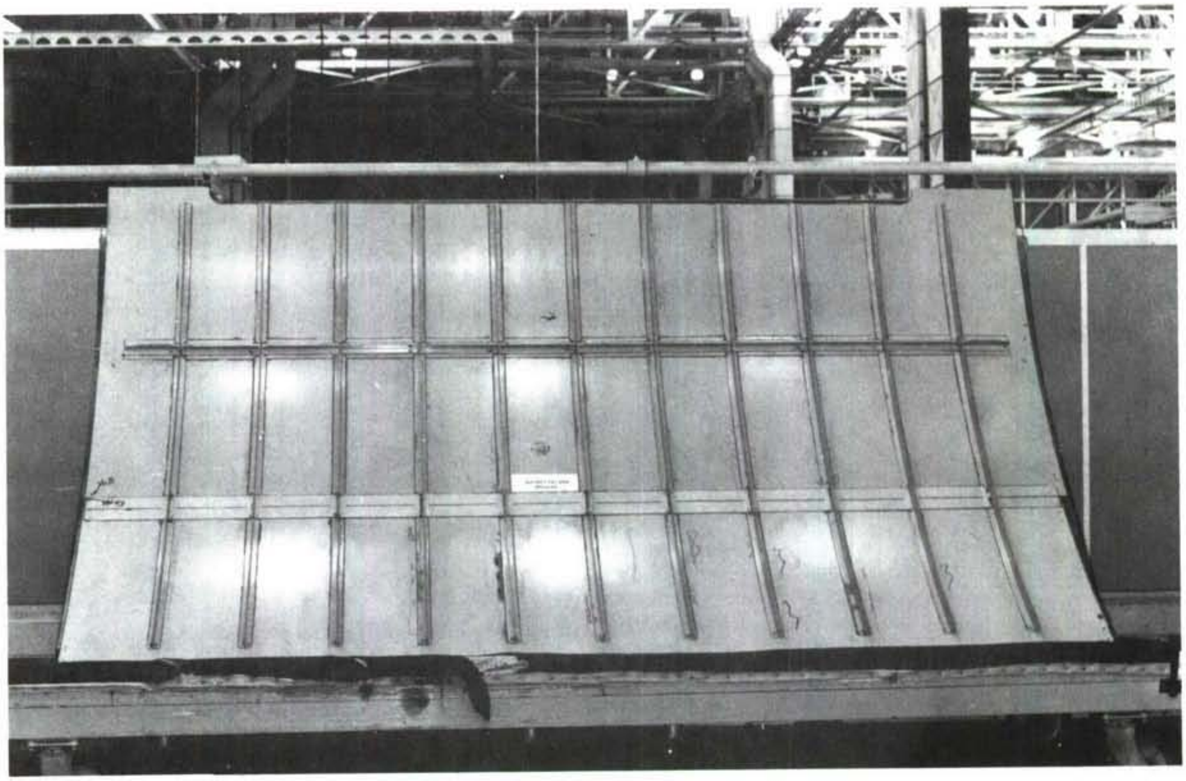


FIGURE 60.

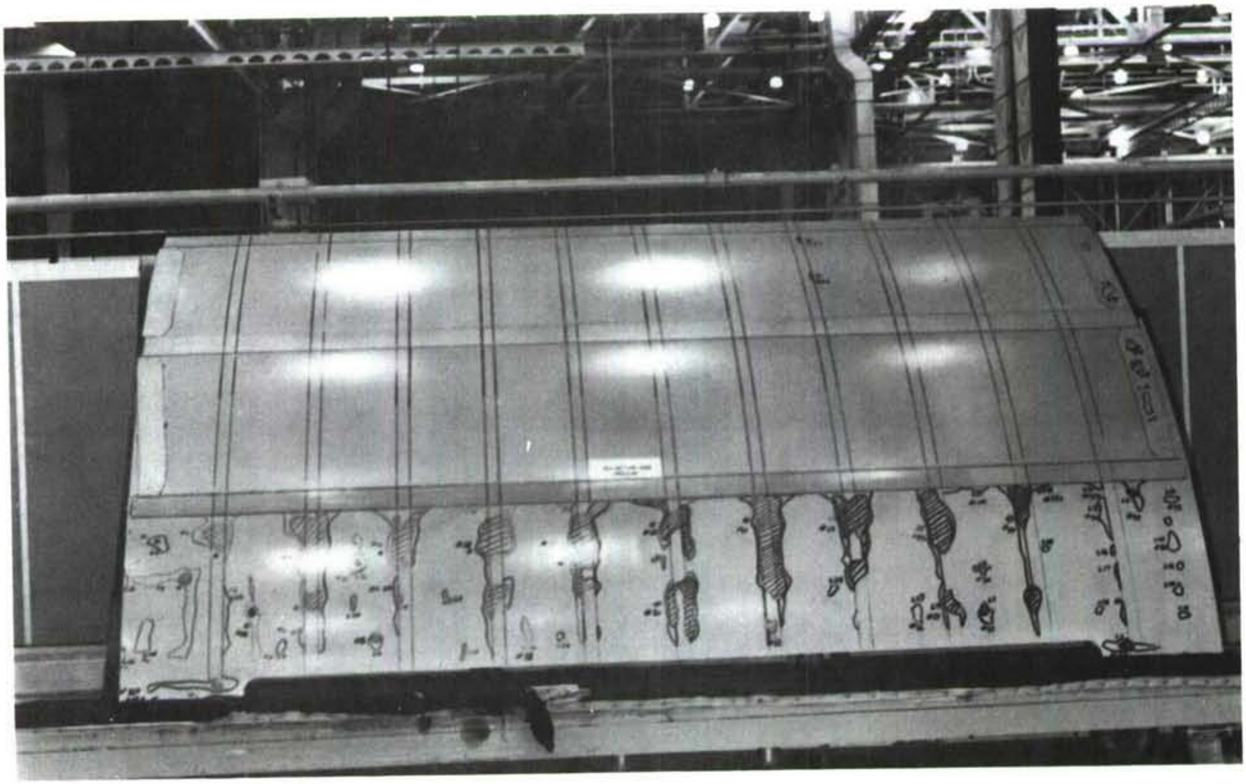


FIGURE 61.

FIGURE 62.

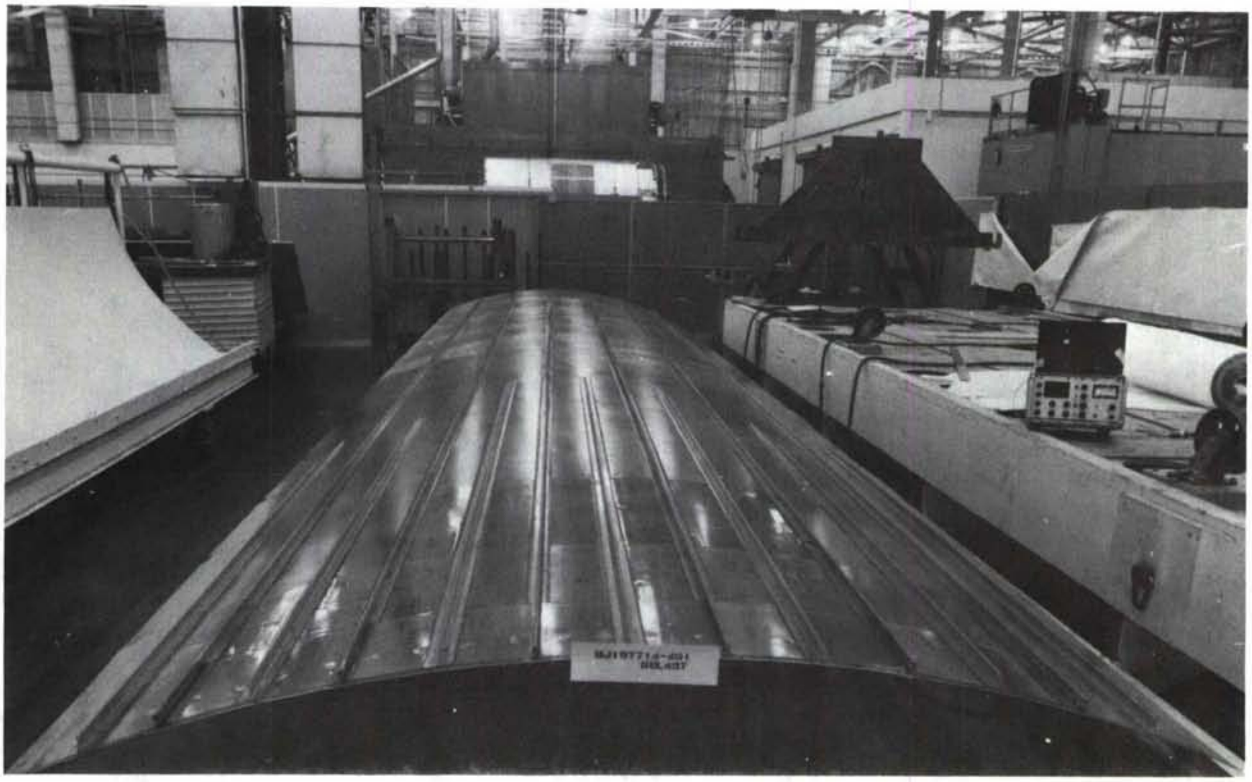


FIGURE 63.

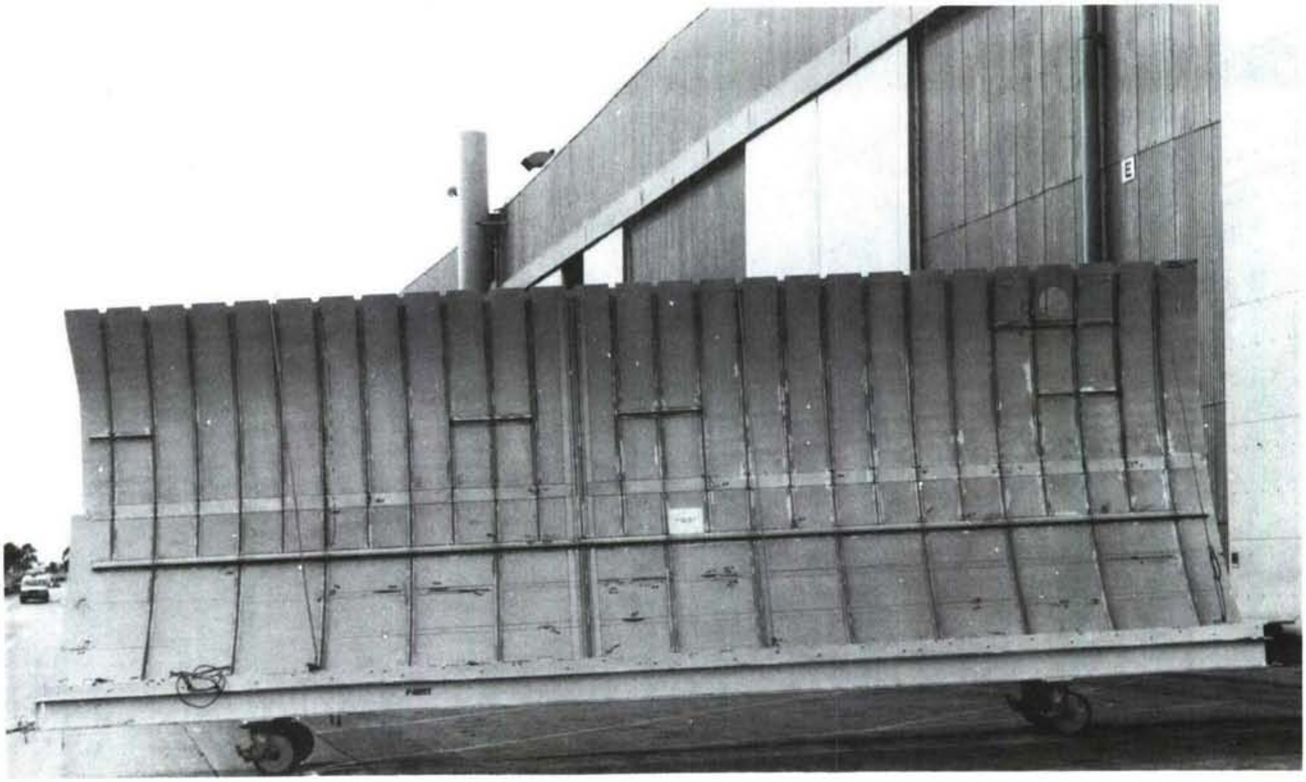


FIGURE 64.

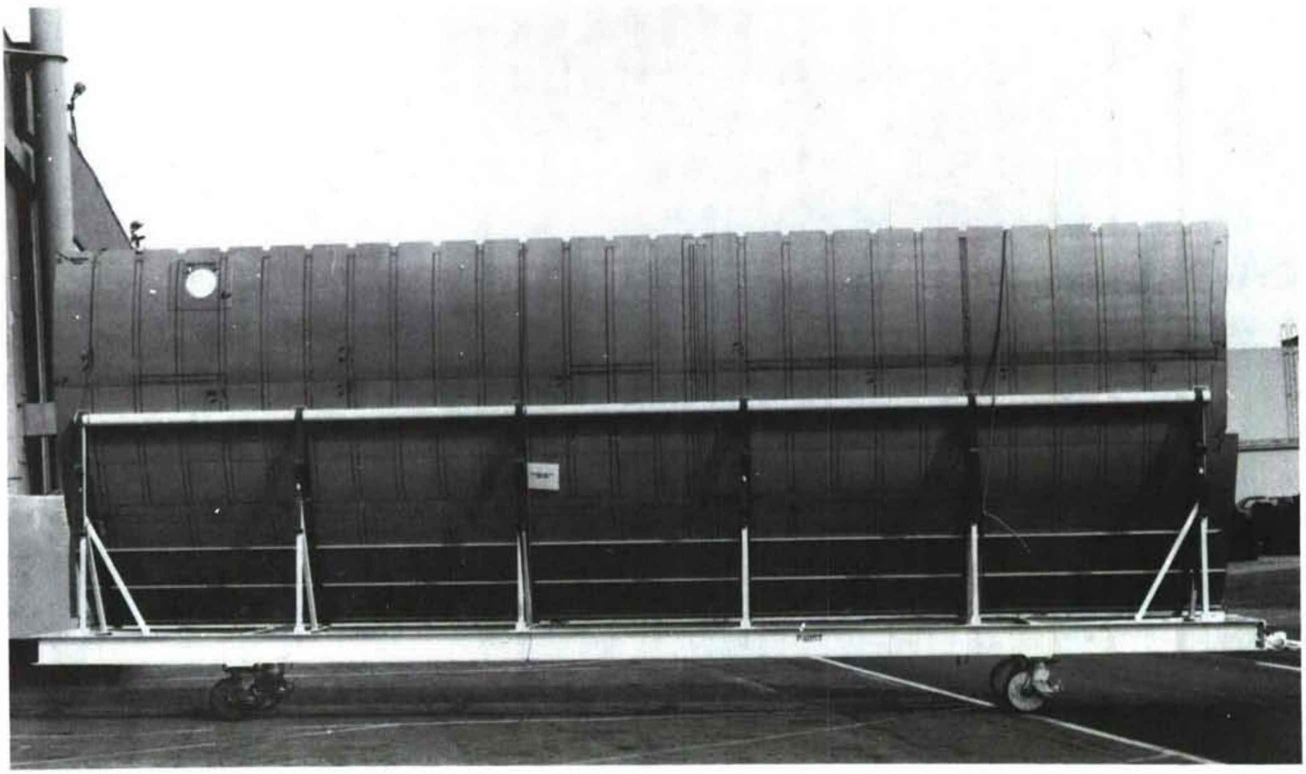


FIGURE 65.

4.22 ASSEMBLY INSPECTION

Standard shop assembly practice was used during assembly of the bonded panels into the FSDC and subsequent mating of the FSDC to the aft and forward steel test fixtures. The bonded panels were assembled via the Assembly Outline (AO). Mandatory inspection points and "buy-offs" were indicated on these AOs.

Key inspection points included: 1) verification of alignment of the bonded panels in the assembly tools, 2) inspection of the drilled rivet patterns, 3) close tolerance hole inspections when required by the ED, 4) inspection of fastener heads after installation, and 5) inspection of faying surface sealant at each mechanical joint. All discrepancies and required rework was documented on FRRs.

4.23 CONFORMANCE INSPECTION

The FSDC was inspected by AMS ADP office personnel prior to initiation of the Full Scale Tests at DAC. The following records were made available for review by the AMS ADP office and were impounded in the PABST Program office for the duration of Phase IV - Full Scale Test.

1. Failure Rejection Reports for the entire program - Phases IB, II, and III.
2. Test data provided by the supplier of traceable materials for the entire program - Phases IB, II, and III.
3. FOs for the FSDC bonded panels.
4. AOs for the complete assembly of the FSDC.
5. Colored and black & white photographs of all FSDC details.
6. Nondestructive test techniques for the bonded panels including pictures showing areas of interest.
7. Engineering control drawings delineating where additional layers of adhesive film were added prior to bonding of the panels.

A thorough Conformance Inspection of the FSDC was made by AMS ADP office personnel accompanied by the DAC PABST Program Manager, the Quality Assurance Manager and the Design Engineering Manager.

The major FSDC assembly problems with their respective fixes, and the rationale for each fix were discussed with the AMS ADP office. These discrepancies and their locations on the FSDC are shown in Figure 66. On 15 June 1978, the AMS ADP office notified the PABST Program Manager that the Conformance Inspection was acceptable, and that DAC could proceed with Phase IV - Full Scale Test.

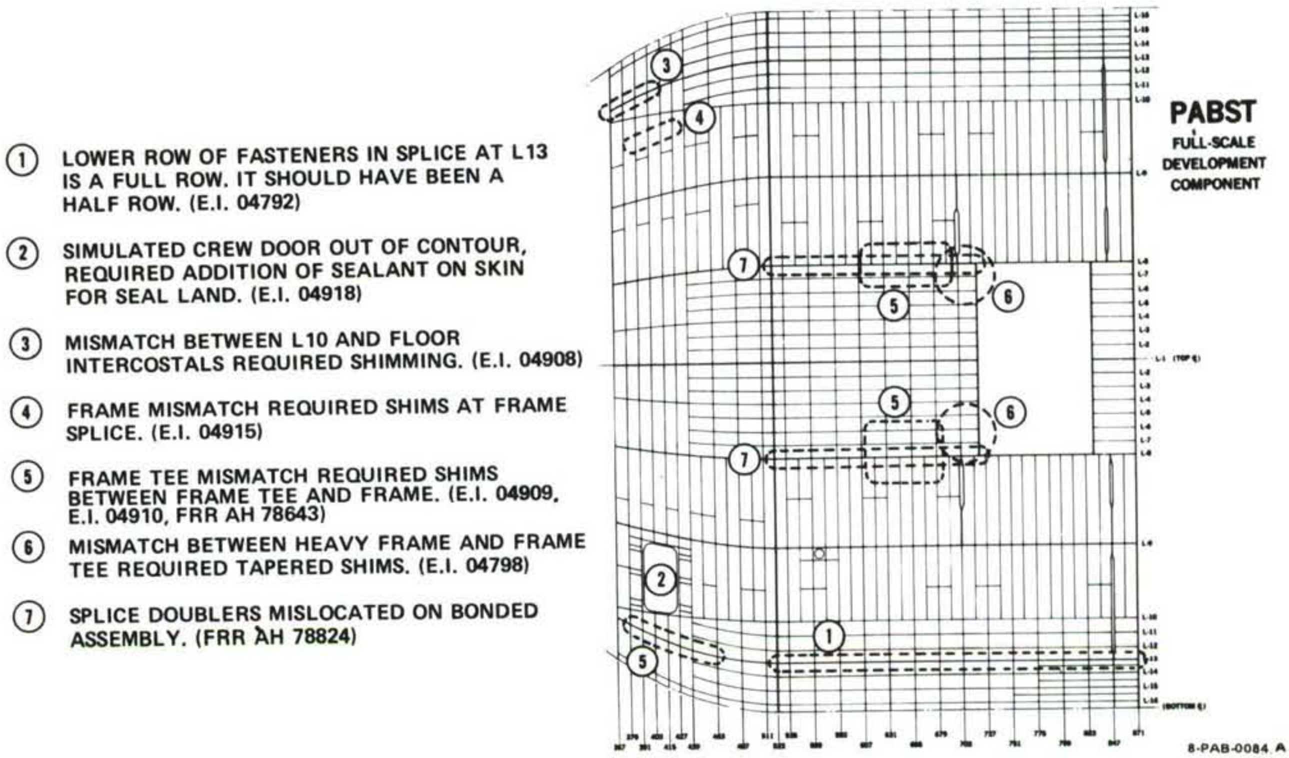


FIGURE 66. ASSEMBLY EXPERIENCE

4.24 QUALITY ASSURANCE IDENTIFIED AREAS OF INTEREST

Recent aerospace industry developments have necessitated additional Quality Assurance controls that would further enhance the durability and integrity of primary structures through the use of adhesive bonding. These areas of interest include:

1) Polarizing lens inspection of the phosphoric acid anodize, 2) Adhesive primer application, 3) Primer thickness verification, 4) Development of moisture absorption detection methods and limits regarding the adhesive film prior to bond, 5) Cure monitoring, 6) Chemical characterization of

the adhesive primer and film, 7) NDT inspection, and 8) Adhesive strength vs. cohesive strength of the bondline.

4.24.1 Anodic Surface Inspections

The importance of the anodic surface and prevention of surface contamination has been discussed previously. The polarizing lens inspection of this uncontaminated surface is presently very subjective and open to human error. For a production mode, a more reliable source of verification would be to use scanning ellipsometry. This method was investigated by Rockwell International as a satellite program of the PABST program. It is conceivable that the optimum anodic surface and the presence of contamination could be detected with this computer aided system. This automated system using the ellipsometer would eliminate the human error factors associated with the polarizing lens and would be capable of inspecting fast-moving details with ease and accuracy.

4.24.2 Adhesive Primer Application

A more uniform coat of adhesive primer can be applied by electro-chemical deposition; commonly termed electrophoresis.

4.24.3 Adhesive Primer Thickness Verification

Primer thickness verification is of primary concern in a production mode. Actual thickness verification of the primed details was not accomplished on this program. As no "state-of-the-art" instruments were available that could effectively be used in a production mode by the in-process inspector. Primer thickness of the details were accepted based on the primer thickness of the wedge crack specimens which were verified in the laboratory.

A reliable instrument must be developed that can be used by the in-process inspector for primer thickness verification.

4.24.4 Moisture Absorption by the Adhesive Film

Moisture absorption by the adhesive film is a concern. Recent tests have shown that moisture pickup by the adhesive film prior to cure has adversely affected the durability of the bond joint. The maximum permissible moisture pickup must be defined for in-process process control inspection. An accurate in-process inspection method for determining this moisture content prior to curing of the adhesive film must be developed.

4.24.5 Cure Monitoring

Cure monitoring devices such as the Audrey machine and Ion graphing should be more fully investigated.

Preliminary investigation with these instruments indicate the period at which autoclave pressure on the assembly should be applied and when cure is complete. These systems provide a more efficient and cost effective cure cycle by reducing the total time at elevated autoclave temperatures.

4.24.6 Chemical Characterization - Incoming Receiving Inspection

Industry is aware of the need for chemical characterization of adhesive primers and films to assure durability. The primary areas of investigation at DAC are HPLC (High Pressure Liquid Chromatography) and Rheology.

HPLC has recently become the accepted industry leader for chemical characterization of epoxy resin systems whereby the resin is dissolved in a solvent, tetrahydrafuran (THF) or variations thereof, and forced with high pressure through the instrument. This method of analysis can be used to quantitatively determine the ratios of the curing agent to the hardener, and then the hardener and curing agent can be independently analyzed to determine that their chemistries are proper for the requirements. Rheology is a broad term describing physical chemistry and the associated change through the curing of the adhesive system.

Chemical characterization is required to ensure the acceptability and durability of the adhesive system.

4.24.7 NDT Inspection

Fokker Bondtest inspection was laborious and time consuming since the maximum inspection area per contact is only 3/8 inch diameter. A better and faster method must be developed to make NDT inspection cost effective in a production environment.

NDT inspection in a production mode could be accomplished as follows:

1) In-motion x-ray if the adhesive film were x-ray opaque.
2) Automatic "C-scan" ultrasonic inspection if not opaque.
3) Verification of suspect areas (x-ray or "C-scan") using the Fokker Model 70 Bondtester.

4.24.8 Adhesive Strength vs. Cohesive Strength

The inherent weakness of NDT inspection is it's present inability to determine the adhesive strength between the adhesive film and the adherend. This problem perplexes all NDT personnel and must be resolved for future programs. The present accepted industry position is to impose stringent in-process Quality Assurance and Manufacturing controls to prevent this problem (low film-to-adherend adhesive strength).

The Fokker Model 70 Bondtester has proven it's capability for measuring the cohesive strength (lack of porosity) of a bondline. M&PE has performed numerous investigative studies demonstrating this capability as published in PABST monthly reports.

SECTION V

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

During the PABST program the female and male (dual pressure) tools were used exclusively in the autoclave. The female tool was used to bond 6 constant section panels; a male tool was used to bond 3 additional constant section panels; and another male tool was used to bond the 10 nonconstant section panels. The difficulties experienced in vacuum bagging the male dual pressure bond tool could be easily overcome by utilization of reusable formed-rubber vacuum bags. By comparison, the female tool is not considered a cost effective approach for production of stiffened panels of the types used on the PABST program. However, the female tool is suitable for bonding light, non-intersecting stiffeners and skin doublers.

The male (dual pressure) bond tool can be further improved for production use by developing mechanical techniques (using a rubber bladder) for applying local pressure to the bonded faying surfaces, and by employing integrated heaters which will allow the assembly to be cured anywhere - without using the autoclave. This would free the autoclave for other uses and allow production of bonded assemblies at a higher rate and a much reduced cost.

The PABST experience with adhesive bonding confirms the old adage - if the parts fit well before bonding, there is no need to inspect the assembly afterwards; and conversely, if the parts do not fit well before bonding there will be no point in bothering to inspect after bonding. The important thing is to have accurate details, handled carefully, and bonded in a tool which encourages fit improvement by deflection of the more flexible details. In such an environment, the amount of prefit work is minimized.

The use of multi-stage bonding, with each stage being simple enough to permit the most straightforward bagging applications without requiring bleeder material, has been pursued far enough to know that it is a very promising approach needing further R&D investigation and development.

Environmental testing demonstrated the need for a corrosion resistant primer. BR-127 primer was the only one shown to be effective, however, techniques for applying it are demanding and precise. The encouraging progress with electro-deposition of primer in a bath should be pursued, to make primer thickness application more consistent and tolerant.

The use of external longerons did not adversely affect stability or performance of the aircraft according to wind tunnel testing, and this design provides important relief from the entrapment of bilge fluids and other corrosive substances.

5.2 RECOMMENDATIONS

1. Large panel assemblies involving up to 120 detail parts of primary fuselage structure can be successfully bonded together and subsequently assemblied into a complete fuselage structure.

2. Detail parts tolerances do not have to be held any closer than for corresponding riveted structure.

3. The dual pressure male bond tool produced a better quality bonded assembly than the female bond tool. This proved that to obtain best results, the tool must support the stiff details rather than the more flexible details.

4. The configuration of the male tool and the arrangement of the detail parts made the developmental application of the vacuum bag material very labor intensive and time consuming, and was therefore not very cost effective. For a production run, a permanent or reusable vacuum bag would need to be developed to make the operation more efficient.

5. The prefit operation for the male bond tool was much simpler and required less rework of the detail parts compared to that experienced with the female tool operation. It is conceivable that using better forming tools, as would be used for a production run, the prefit operation could be minimized.

6. Each type of bonded panel had the prefit operation confirmed by a verifilm cure cycle as required by military specification during the PABST program. For a production run, this verifilming operation would be eliminated. The key to a good bonded assembly is to have proper fit between the details prior to bonding.

7. The use of phosphoric acid anodize for surface preparation proved to be an easily controlled operation in the production environment. However, one critical phase involves the racking or supporting of the details on the processing frame because good electrical contact is mandatory to produce good results. Intermittent electrical contact results in a thin oxide coating which is not easily detected and may produce adhesive failures under load. Springs and clips were utilized to provide tension on details and maximize electrical contact forces.

8. The program determined that anodized or etched surfaces can be easily contaminated, even when handled with white cotton gloves or neutral kraft paper prior to application of the primer. Therefore, the racked parts from the process line should be inspected for proper anodize, be immediately primed, and the primer must cured completely before the details are removed from the supporting rack.

9. The adhesive primer, BR-127, has proven to be the most effective interface between the anodized surface and the adhesive. The primer application is a critical step because of the thin (.0001 to .0003 inch) coating required and the presence of strontium chromate. Because these crystals settle out of solution rapidly, proper application of the primer required that the primer be continuously agitated inside the pressure pot and applied by a recirculating spray gun operated by a skilled person. Improper application of the primer required subsequent stripping and reprocessing of the details which was a costly operation.

10. Because the FM-73 adhesive is hygroscopic, the adhesive storage and application requires a room with a low moisture content. Maximum limitations are not yet established, but as little as one percent moisture content in the adhesive before bonding can be catastrophic to the adhesive's environmental cycle durability performance.

11. During the cure cycle, the maximum heat-up rates of the selected adhesive must be observed because some adhesives become frothy when heated too rapidly which causes porosity and low bond strengths in the bondlines.

12. Because of the high flow characteristics of the new generation 250^{o}F cure adhesives, control procedures must be developed so that NDI inspection can be performed after cure without a flash removal operation.

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